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Review

Recent Progress in Hybrid Aluminum Composite: Manufacturing and Application

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Abstract: Due to their excellent properties, the requirement for materials with higher characteristics has transformed primary alloy into composite materials. Composites are particularly essential for various applications in numerous engineering purposes because of their superior mechanical, physical, and machining qualities. Compared to traditional materials, aluminum composite has various advantages and superior characteristics. To reduce production costs and obtain the desired properties, the researchers developed a hybrid aluminum matrix composite (HAMC), an AMC with two or more types of reinforcement. Further studies were conducted to improve the qualities and manufacturing processes of composites to improve their properties. Various methods are available to HAMC manufacturing, and different manufacturing methods result in different characteristics of HAMC composites, viewed from physical properties, mechanical properties, and production cost. In addition, differences in the type, size, and amount of reinforcement produce various hybrid composite properties, especially in the physical properties, mechanical properties, and tribological behavior of HAMC. This work presents a comprehensive review of recent progress in HAMC study with various reinforcement particles, manufacturing techniques, physical, mechanical, and tribological properties of HAMC. On the other side, this work provides discussion for application, challenges, and future work conducted for HAMC development.

Keywords: aluminum matrix composite; hybrid; manufacturing; application

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1. Introduction

The need for materials with a light strength-to-weight ratio rises year by year. Researchers have developed numerous materials to respond to this difficulty, particularly the composite metal matrix (MMC). Because of its exceptional qualities, such as low density, high specific strength, corrosion resistance, high stiffness, good stability at high temperatures, reduced part weight, low thermal shock, and the capacity to improve mechanical properties, AMC is widely used in a variety of applications [1–3]. MMC is a wide-reaching material for various applications, such as defense, transport, maritime, aerospace, medical, and other industry [4,5]. Aluminum alloys have shown to be particularly promising for reducing automotive weight in recent years. In engine applications, AMC has been found to reduce total weight, fuel consumption, and emissions of cars and aircraft [6,7]. Various brands, such as Toyota, Boeing, and General Motors, have used AMC in some of their products [8–10].

AMC is a material made of an aluminum matrix and strengthened with ceramic or other materials. Reinforcement refers to the addition of ceramic or other elements to a composite. Metal has been reinforced to increase its characteristics to meet the requirements. SiC [11], Al_2O_3 [12], TiO_2 [13], and graphite [14] are common reinforcement materials used in AMC. However, researchers have created AMC reinforced with industrial waste, agricultural waste, and other natural resources such as fly ash, aloe vera powder, bottom ash, rice husk ash, bamboo leaf ash, red mud, and sea sand [15–21]. The use of reinforcement and others in AMC has been carried out with a single reinforcement. However, with the increasing qualification of the material required, a hybrid aluminum matrix composite (HAMC) has been developed. HAMC is the second generation of AMC with superior physical and mechanical properties compared to single reinforcement AMC, in which the metal is aluminum with a high percentage and two or more reinforcements [22,23]. Depending on the amount and size of the reinforcement supplied to the aluminum matrix, combining various reinforcements can result in HAMC advantages [24]. The additional primary reinforcement improves the basic properties, whereas secondary reinforcement obtains the desired composite properties [25]. As a result, HAMC can replace traditional aluminum in a variety of industrial applications. Furthermore, HAMC is the second generation of composites that can replace single-reinforced composites due to their improved properties [26].

HAMC is classified into three types, based on the type of reinforcement: a combination of two synthetic ceramic reinforcements, synthetic ceramic reinforcement and agricultural waste, and synthetic ceramic reinforcement and industrial waste [15]. As a result, the hybrid composite could be a better substitute material for various advanced applications. Moreover, hybrid aluminum composites have largely supplanted ordinary aluminum in a variety of applications. This paper reports the HAMC investigations conducted to be considered for the development of HAMCs with superior qualities.

2. HAMC Fabrication Process

The fabrication process for HAMC is widely categorized into two processing techniques: solid-state processing and liquid-state processing shown in Figure 1. Mechanical properties, such as hardness, tensile strength, fatigue resistance, impact strength, and cost effectiveness, are all affected by the fabrication process.

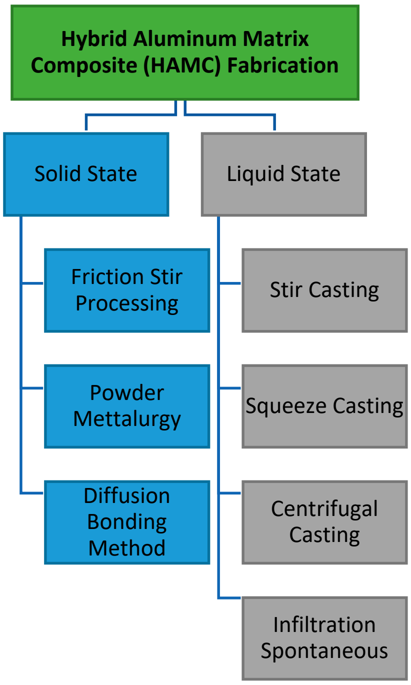

Figure 1. Fabrication process on the HAMC.

2.1. Solid-State Processing

The solid-state fabrication of MMCs entails attaching matrix material and reinforcements in solid states at higher temperatures and pressures due to mutual diffusion in solid state processes, whereas the fabrication of particulate-reinforced AMCs entails blending the elemental powders in a series of steps followed by consolidation [27]. Aluminum matrix composites (AMCs) can be manufactured via solid-state processing such as friction stir processing (FSP), diffusion bonding, or powder metallurgy [25]. Composites of aluminum matrix enhanced with ceramic particulates can be processed reasonably quickly and are almost isotropic compared to reinforced fiber composites [28]. Some processes that are used for the manufacturing of MMC are discussed in this section.

2.1.1. Friction Stir Processing (FSP)

Friction stir (FSP) is an efficient manufacturing method to deal with melt-based process restrictions [29]. FSP is an excellent approach for producing surface and bulk composites [30]. This process eliminated porosity, the fragmentation of Al dendrites, the breakage and redistribution of Si particles, and grain refinement. The FSP operating principle has been taken from Welding Institute (TWI)-invented friction stir welding (FSW) due to the frictional heat and the transfer of material across the tool. FSP is an environmentally benign technique because the process temperature is kept below the melting point of the work material. The spinning tool is plunged into the base metal and progresses at a constant rotational and traverse speed during the manufacturing process, so that FSP causes severe plastic deformation and material flow [31].

The following parameters control the FSP process: rotational tool speed (TRS), tool traverse speed (TTS), tool shoulder diameter (TSD), feed rate, tool tilt angle (TTA), plunging force, tool pin profile, and the number of passes. As the number of passes rises, the powder distribution becomes more homogeneous, and increasing the number of FSP passes reduces the particle cluster size, thereby enhancing the properties. Nevertheless, two metal plates are not joined by FPS. It only offers a surface composite preparation that results in a refined grain structure that improves properties such as hardness and superplasticity [32]. In any material, fine grain microstructure is a determining factor in achieving superplastic behavior. Furthermore, the heat input affects the grain of the FSP sample [33]. The particle size, volume, and type are the main characteristics that increase hardness [34]. In the FSP approach, as shown in Figure 2, V is the instrument's explore speed, and x is its rotational speed. The tool is portrayed as a green-colored object in Figure 2, and it is a stiff, solid object. The workpiece, defined as a blue-colored object, is a ductile material with elasticity, plasticity, and the ability to harden kinetically. The square pin's contact area with the base metal is comparatively higher, which helps generate more frictional heat shown in an orange-colored object. Microstructures of both the surface hybrid composites are uniformly dispersed in the nugget zone (NZ), as shown in light blue color. A spinning tool is plunged into the base metal during the fabrication process and advanced at a constant rotational and translational speed.

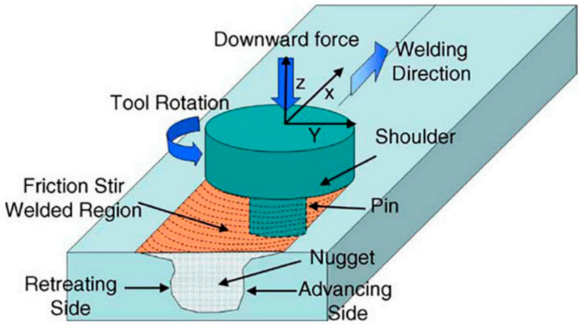

Figure 2. The process of FSP [35].

Subramani et al. [35] investigated hybrid composite Al6061 and its reinforcements B4C and SiC_p particles fabricated by friction stir processing (FSP) technique. The results indicated that the uniform distribution of SiC_p/B4C elements in the A6061 matrix by FSP process and heat treatment could be advancing the mechanical possessions of samples.

Harish et al. [36] studied the microhardness test and wear behavior test to evaluate the surface of Al5056/bagasse ash/SiC hybrid composite during friction stir processing.

Bagasse ash is used in various quantities of 3, 4, 6, and 9 wt.%, while SiC is employed in a constant proportion of 3 wt.%. From the experiment, we know that bagasse ash helps increase the sustainability of the environment through waste disposal. The result shows that the wear rate decreases as the composition of the reinforcing material increases [37], and the agglomeration of reinforcement particles causes a minor loss in hardness at higher reinforcement compositions.

Kumar et al. [38] studied the various properties by varying the % of alumina and aluminum nitride in the AA6061. This study aims to determine the effect of varying reinforcement in the microstructure and hardness of friction-processed 6061 plates. The result shows that FSP refines the grain size of the aluminum alloy. Furthermore, micrographic shows that the surface composite layer is very well bonded to the aluminum alloy substrate, with no flaws observable at the interface. The hybrid surface composite exhibits greater hardness than the surface composite created using a single ceramic particle for various percentage compositions of reinforcement material. To evaluate the hardness specimen, the Rockwell Hardness Test is used; the hardness value is shown in Table 1. From the table, we know that is the composite with the composition 50% Al_2O_3 and 50% AlN have higher hardness than those made with other compositions.

Table 1. Hardness value of AA6061 reinforced with Al_2O_3 and AlN [38].

Specimen	Microhardness (HRB)			
	Base Metal	Average	Stir Zone	Average
1. FSP of AA6061	B-89 B-85 B-88	B-87.33	B-91 B-88 B-89	B-89.33
2. 75% Al_2O_3 & 25% AlN	B-87 B-91 B-85	B-87.66	B-93 B-87 B-94	B-91.33
3. 50% Al_2O_3 & 50% AlN	B-89 B-87 B-85	B-87	B-94 B-92 B-93	B-93
4. 25% Al_2O_3 & 75% AlN	B-88 B-85 B-91	B-88	B-89 B-87 B-91	B-88.66

Devaraju et al. [39] fabricated 6061-T6 with a mixture of (SiC+Gr) and (SiC+Al_2O_3) particles of 20 μm in average size using FSP. The results show that both surface composite microstructures show that SiC, Gr, and Al_2O_3 are spread uniformly in the nugget area (NZ). They discovered that combining Gr particles with SiC particles, rather than Al_2O_3 particles, reduces microhardness while significantly increasing dry slide wear resistance of aluminum alloy 6061-T6 surface hybrid composite. Microhardness and wear characteristics were observed to be associated with microstructures and micrographs.

Soleymani et al. [37] prepared MMC from FSP for material fabrication. This research aimed to investigate a self-lubricating and wear-resistant surface hybrid Al-based composite reinforced with a mixture of SiC and MoS2 particles. The investigations showed that reinforcing particles were distributed uniformly in a processed zone and that the layer of surface processed with the base material was well bonded. The tribological investigations have demonstrated that hybrid composite surface has the most excellent wear resistance compared with other samples. Dominant wear processes were investigated that operate under dry sliding sample circumstances.

Patel et al. [33] conducted a hybrid technique, which is based on the FSP cooled air compressed, to detect effects on process temperature and resulting microstructure compared to standard FSP; a 7075-T6 aluminum plate was used for this investigation. The hybrid FSP with compressed air cooling created a perfectly fine equiaxed grain microstructure in the SZ. Compared to typical FPS, the hybrid sample generated less heat input, which inhibited grain growth during the process and eventually reduced grain size and caused an elongated grain shape. As a result, compressed air-assisted FPS produces fine microstructure in the stir zone. It can be promoted to achieve the superplastic behavior of 7075Al alloy. Because of the lower heat input during the process, the hybrid FSP slightly improved average SZ microhardness. The recent work on the FSP process studies of hybrid aluminum matrix composite has been critically studied, and their findings are reported in the following Table 2 comprehensively.

Table 2. Research article about friction stir processing.

Year	Writers	Matrix	Reinforcement	Findings
2021 [35]	Subramani et al.	Al6061	B_4C and SiCp	The uniform distribution of SiCp/B_4C components in A6061 matrix achieved through the FSP method and heat treatment can improve mechanical properties.
2021 [36]	Harish et al.	AL5056	Bagasse ash (3, 4, 6, and 9 wt.%) and SiC (3 wt.%)	When the bagasse ash concentration was increased to 6%, the characteristics improved.
2016 [33]	Patel et al.	Aluminum 7075	-	The compressed-air cooling Hybrid FSP provided a perfectly matched granular microstructure within the SZ.
2013 [39]	Devaraju et al.	6061-T6	(SiC+Gr) and (SiC+ Al_2O_3) particles of 20 µm	Microstructures and worn micrographs are connected to microhardness and wear characteristics.
2012 [37]	Soleymani et al.	Al5083	SiC and MoS_2	The hybrids were used concurrently with the light delamination and the light abrasion mechanisms. Wear mechanisms confirmed that hybrid composite production may reduce wear damage greatly at the surface and increase alloy wear resistance.

2.1.2. Powder Metallurgy

Powder metallurgy is the most widespread solid-state processing method, since this technique was designed, developed, and applied over traditional metallurgy before being applied to metal matrix composites [40]. Powder metallurgy has advantages, including fabricating complex shapes with precise dimensions, uniform distribution of reinforcements, less scrap loss, less machining, and lower porosity at a low cost [41]. Powder metallurgy processing technology is desirable because it uses lower temperatures and theoretically better interface kinetics control. The processing technique also allows matrix alloy compositions and microstructural refinement to be applied only through rapidly compacting powders. Metal powders are mixed with reinforcement materials (ball, planetary, high-enemy mill). The metals powders are then compacted in a die and sintered [42] using hydraulic presses, summarized in Figure 3.

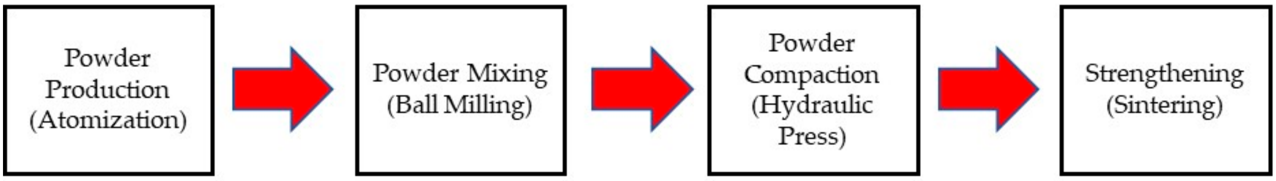

Figure 3. Processing route of powder metallurgy.

Ashrafi et al. [22] fabricated the hybrid reinforcement (Fe_3O_4–SiC) novel composite via the powder metallurgy process. The goal of this study was to determine the effect of Fe_3O_4–SiC nanoparticles on the microstructural, thermal, electrical, and magnetic properties of the composite. The result shows that adding SiC changed the microstructure from the plate-like flakes to spherical, as shown in Figure 4. The possibility of agglomeration at grain boundaries was increased by increasing the weight percentage of reinforcements. Related with magnetic properties of Al–Fe_3O_4–SiC composites, we know that adding a high amount of Fe_3O_4 nanoparticles might result in higher magnetization (Ms); increasing the amount of iron oxide can cause mechanical degradation.

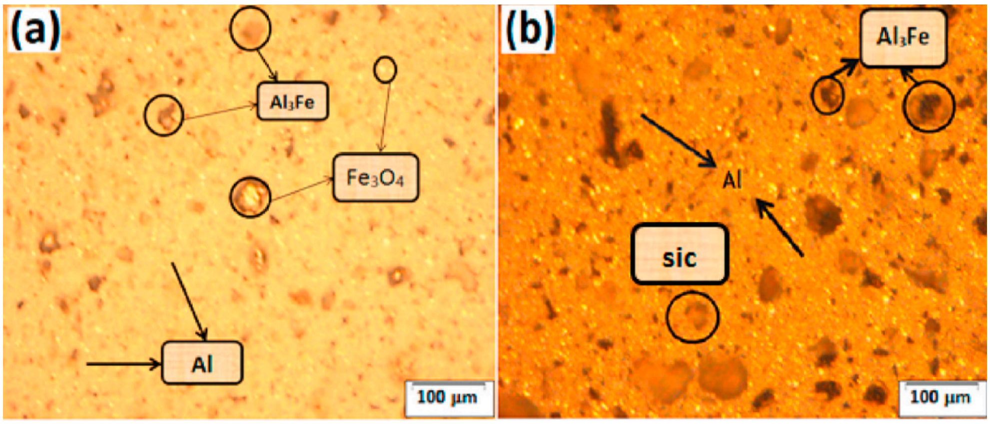

Figure 4. Optical microscopy of (**a**) Al–15 Fe_3O_4 and (**b**) Al–15 Fe_3O_4–30SiC [22].

Zhang et al. [43] investigated the effect of SiC–graphite and SiC–graphene nanosheets (GNSs) were incorporated into aluminum matrix composites using powder metallurgy and reported that the addition of SiC–GNSs particle intensifies the deformation of the aluminum particles compared with SiC graphite, and furthermore, nanostructured composite (57.7 nm) was successfully produced upon the addition of SiC–GNSs.

Tang et al. [44] developed contents of SiC and stainless-steel particles through powder metallurgy route with various artificial aging treatment. The experiment can be summarized as follows: stainless-steel particles increased the ductility of the hybrid-reinforced composites without reducing their strength. The mechanical properties of 6061 aluminum matrix composites are clearly affected by various artificial age treatments. The fracture surface breakage of stainless-steel particles indicated that load could be effectively transferred from the matrix to the stainless-steel particles, enhancing the ductility of hybrid composites. The stainless-steel particles have no effect on the aging characteristics of the composite Al 6061 alloy matrix. The homogeneous strain distribution inside the hybrid composites was primarily responsible for the increasing ductility.

The powder metallurgy process of aluminum reinforced with SiC–B_4C particle was investigated by Bodukuri et al. [42], and three different combinations of compositions in volume fraction were chosen, namely, 90%Al 8%SiC 2%B_4C, 90%Al 5%SiC 5%B_4C, and 90%Al 3%SiC 7%B_4C. An attempt was made to investigate the properties of the developed metal matrix composite. The micro-hardness of the metal matrix composite increased significantly as the percentage of B_4C increased. The prepared metal matrix composite's microstructure reveals a uniform distribution of particles in the metal matrix.

The latest work on powder metallurgy (PM) process investigations of hybrid aluminum matrix composite has been thoroughly examined, and the results are given in detail in Table 3.

Table 3. Research articles about powder metallurgy.

Year	Writers	Matrix	Reinforcement	Findings
2021 [22]	Ashrafi et al.	Al	Fe_3O_4–SiC	Adding Fe_3O_4 nanoparticles and SiC hybrid reinforcements in the aluminum matrix improved the magnetic permeability; increasing the SiC improved the thermal conductivity of aluminum by 37%.
2021 [44]	Tang et al.	6061-Al	SiC and stainless-steel particles	The composite hybrid reinforced with SiC and stainless-steel particles could successfully increase ductility without sacrificing strength.
2020 [43]	Zhang et al.	A355	SiC–graphite and SiC–graphene nanosheets (GNSs)	The addition of SiC–GNSs particle intensifies the deformation of the aluminum particles compared with SiC–graphite.
2016 [42]	Bodukuri et al.	Al	SiC–B_4C	The hardness of composite increased significantly as the percentage of B_4C increased.

2.1.3. Diffusion Bonding Method

Diffusion bonding is a solid-state process in which the connected components experience macroscopic deformation of little more than a few percent, and there is no liquid phase. Diffusion bonding occurs due to the bound materials' interface atoms diffusing to encourage atomic mobility and guarantee a full metallurgical connection. The procedure relies on several factors, including time, applied pressure, and bonding temperature [45]. Due to the development of a brittle compound layer and a build-up of oxygen impurities in copper at the bond interface, structurally sound diffusion bonding is difficult to produce when combining stainless steel and copper alloys. Insert material is utilized to increase bonding strength; typically, a thin layer of Ni-based alloy is placed between the stainless steel and copper alloy surfaces.

Diffusion bonding is a desirable manufacturing method for aerospace applications requiring mechanical properties in the bond zone and a solid metallurgical connection. The findings show that the diffusion-bonding method has been successfully applied to the production of aerospace components, such as titanium sandwich panels, high-pressure vessels for spacecraft control, hollow fuel vessels, and steel combustion chambers. Thin sheets with blow forming are the most often used diffusion-bonding method in aircraft manufacturing [46]. Recent diffusion-bonding research has concentrated on the critical challenges of decreasing the weight of aircraft components and enabling cost-effective production.

The formation of solidification fractures and severe distortion strains may be avoided by utilizing vacuum diffusion bonding and regulating the duration and temperature [47]. In this method, bonding temperature, pressure, holding duration, and surface roughness all play a part in determining joint strength. The development and expansion of intermetallic phases must be precisely regulated in order to achieve maximal strength.

Table 4 summarizes the different techniques, emphasizing relative references to the published works.

Table 4. The summary of solid-state processing.

Manufacturing Method	Method	Influential Variables	Advantages
FSP	1. Reinforcing material as a solvent is created to make a thin coat over the bottom metal. 2. FSPed reinforcing material is packed in a groove made in the base metal and covered by another base metal plate, and, therefore, FSPed reinforcing material is packed in a groove made in the base metal.	Rotational speed, axial load, speed of power travel, hole pattern and geometry, and the number of FSP passes [34,38].	High reproducibility, fast production time, low energy input, refined grain structure, the surface composite layer appears to be very well bonded to the aluminum alloy substrate, no defects are visible at the interface, eradication of porosity, fragmentation of a-Al dendrites, breakage and redistribution of Si particles [29,35,38].
Powder Metallurgy	Fine powders are mixed and blended together in the powder metallurgy process, then degassed in a vacuum and compacted in the desired shape before sintering in a controlled atmosphere. Powder metallurgy is recommended for the manufacture of complex shaped precision components with superior mechanical and structural qualities and high homogeneity.	Volume fraction of reinforcements, green density, compact pressure, sintered density, hot pressing temperature [28,48].	Economical process for complex part production with high strength, dimensional accuracy, minimum scrap loss, high homogeneity, better mechanical and structural properties, and less subsequent machining operations [28].
Diffusion Bonding Method	The technique is used to apply the required pressure to combine comparable or different metal layers and fibers into sandwich metal.	Bonding temperature, pressure, holding duration and surface roughness, temperature, pressure, and the diffusion timing [49]	With various metal matrix composites, it is possible to regulate fiber orientation by varying the metal volume fraction.

2.2. Liquid-State Processing

Many businesses employ the liquid-state technique to create MMCs due to its simplicity and low cost. It requires spreading the reinforcing phase into the molten metal matrix, followed by solidification in the liquid state. Examples include stir casting, composite casting, squeeze casting, and other liquid-state processing processes. Several studies on liquid-state processing of aluminum-based composites were conducted, with the results as follows.

2.2.1. Stir Casting

The hybrid composite stir casting route is the best process and is the most suitable and reasonably priced out of all the methods because it is very simple, flexible, able to produce large near-net shape parts, complicated shapes, and results in less damage, higher yield strength, less effort, and high production rates [25,50,51]. In this process, the reinforcement is stirred into molten metal during the stir casting phase of the composite manufacture. The process of casting involves the generation of a melt of the chosen material matrix, the introduction of a reinforcing material into the melt, and the achievement of a proper dispersion by agitation. Stir casting may therefore produce composites with reinforcement compositions of up to 30% of the volume percentage. The strategic element during this process is mechanical stirring; the vortex technique is the most effective, simple, and commercially used method among all the stir casting routes involving the introduction of a rotating impeller of pretreated ceramic particles into the molten alloy vortex [52]. Figure 5 shows the stir casting setup.

Figure 5. Stir casting setup.

Ünlü [53] compared PM and casting procedures in their research and the work concluded that the casting process had better mechanical qualities than the powder metallurgy method. However, improper control of process parameters in this method can cause problems, such as (a) porosity; (b) insufficient bonding between reinforcement and matrix; (c) the difficulty of achieving uniform distribution of the particulate; (c) poor wettability of matrix and reinforcement; (d) chemical reaction between the reinforcement material and the matrix alloy; and (e) agglomeration due to differences density between matrix and reinforcement [54,55]. To anticipate this, attention is paid to manufacturing process factors such as sink size, stirring time, impeller capacity and size, molten metal temperature, melting duration, stirring speed, reinforcement type/size/%, melting rate, and mold temperature [56]. It is critical to pay attention to the distribution of reinforcing particles in the matrix throughout the stir casting process. In general, the density difference between the matrix and the reinforcement makes uniform distribution between the matrix and the reinforcement challenging. Figure 6 depicts the variables that influence casting quality.

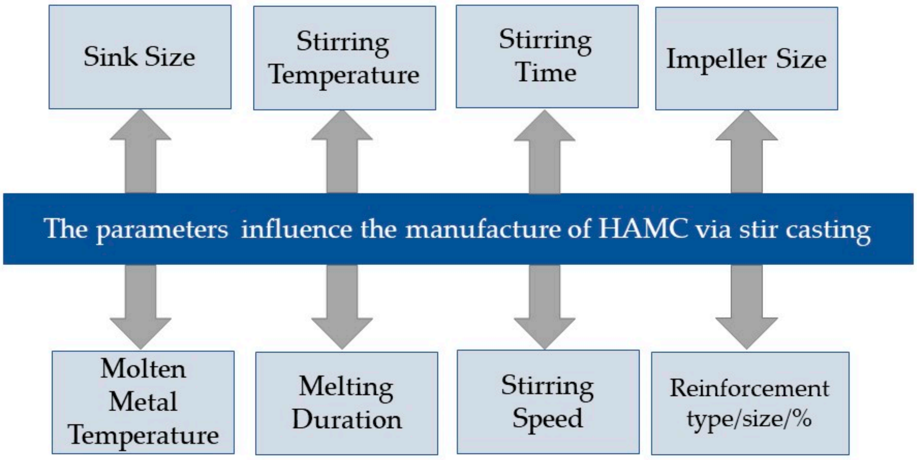

Figure 6. Factors that influence the stir casting process.

Ceramic particle-reinforced aluminum alloy matrix composites are common in the aerospace and automotive industries. The strength of an aluminum alloy matrix composite is determined by the size of the reinforcement and the spacing between the particles. The micro-ceramic particles are incorporated as reinforcement into the liquid metal matrix to manufacture the composite material for significant improvement in composite material strength but decrease elongation. Recently, nano-ceramic particles were introduced to fabricate metal matrix composites, and it has been demonstrated that the effect of size of ceramic reinforcements plays a critical role in the composite material properties, notably enhancing the base material properties while maintaining beneficial elongation and high resistance to temperature creep [57,58]. The quality of metal matrix nanocomposites is entirely dependent on the distribution and dispersion of ceramic nanoparticles in liquid metal.

Lina et al. [59] investigated the impact of stirring temperature and time on ABOw and SiCp hybrid-reinforced 6061 AMC. Figure 7 depicts the distribution on the microstructure. ABO_w and SiC_p agglomerations can be seen in composites in Figure 7a,d, and it can be seen that the uniformity of the reinforcement distribution initially increases and then decreases with decreasing the stirring temperature and increasing the stirring time. The effect is caused by friction and shear between the reinforcement and the semisolid slurry, which is proportional to the viscosity. Reduced stirring temperature increases the solid fraction and viscosity of the semi-solid slurry. At 680 °C, the low viscosity and friction between liquid metal and reinforcements are detrimental to the distribution of reinforcements in composites. Furthermore, at high temperatures, molten metal oxidation and harmful interfacial reactions between SiCp and matrix alloy occur, resulting in particle agglomeration. The solid fraction (52.7%) and viscosity of the semi-solid slurry significantly increase at a lower stirring temperature of 640 °C, but the slurry remains liquid during stirring. The matrix alloy is no longer in a liquid state during stirring when the temperature is reduced to 630 °C, and it is difficult to stir entirely due to greatly increased viscosity or friction resistance, making uniform reinforcement distribution in the composites impossible. Based on the results of the experiment, we can conclude that the optimal stirring parameters are 640 and 30 min, respectively, based on the microstructure and tensile properties.

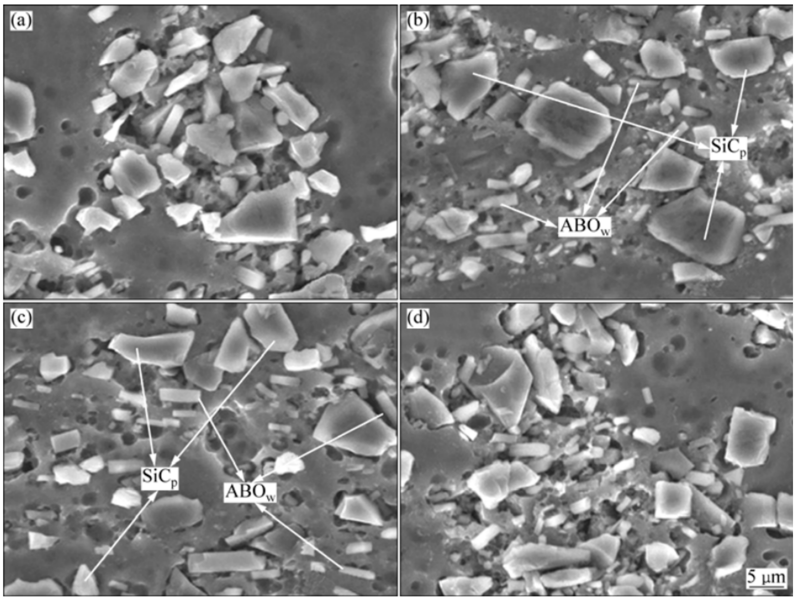

Figure 7. Micrographs of $(5\%ABO_w + 15\%SiC_p)/6061Al$ composites fabricated at different stirring temperatures for 30 min: (**a**) 680 °C; (**b**) 650 °C; (**c**) 640 °C; (**d**) 630 °C [59].

In one study [60], TiC and graphite-reinforced Al 7075 were developed via stir casting. In this experimental, TiC reinforcement varied by 1–4 %wt. Based on the experimental results, it was found that the addition of TiC and graphite to AHC increased the hardness and tensile strength of the composite. Wear resistance from TiC and graphite-reinforced showed an increase with increasing TiC content whereas 4 wt.% of TiC-reinforced showed maximum wear resistance.

Yashpal et al. [61] investigated Al6061, alumina as primary reinforcement, and bagasse ash as secondary reinforcement. The results show that tensile strength, hardness, and impact strength were decreased as the particle size of bagasse ash increased. Smaller particle-reinforced has higher hardness due to bonding between matrix and reinforcement resulted by better wettability. Moreover, the microstructural images show uniform distribution of the reinforcement in aluminum. The increase in the mechanical properties such as hardness, impact, and strength of composite due to the smaller reinforcement particle size also has been reported by Mathur et al. [62]. Larger flaws and more defects are statistically more likely to exist in larger particles, reducing the strength of composites when compared to composites containing smaller particles. Smaller grain size in composites with smaller reinforcement particles can also contribute to increased strength. The usage of bagasse ash, an industrial waste, promotes the concept of reuse.

Vijaybabu et al. [63] fabricated an Al7075 as matrix, B_4C constant (2%), and fly ash (2%, 4%, 6%) by stir casting technique and evaluated the mechanical properties such as tensile strength hardness, impact strength, and density of the composite. Fly ash is an ignition coal product made up of particulates, which are finely carved burning fuel particles. With changes in configuration and the source of the coal being burned, the content of fly ash can alter. As a result, fly ash, which has high thermal and chemical stability, is employed as a reinforcing material. The hardness, elongation, density, and tensile strength increased with the increase in fly ash content. The addition of B_4C improves the hardness of composite but the addition of ceramic particles along with fly ash gives the material much better properties [24]. From the study of impact test results, it was revealed that the amount of energy absorbed by the prepared composite remained the same from samples 1 to sample 3, but increased in sample 4 (Al7075 + 2%B_4C + 6% fly ash).

Suresh et al. [64] established LM25 aluminum alloy-based MMCs reinforced with boron carbide (B_4C), graphite (Gr), and iron oxide (Fe_3O_4) by stir casting process. These composite materials' tribological and mechanical properties were investigated. The microstructural investigation of this composite showed a uniform distribution of reinforcing particles, which indicated that stir casting technique was successfully developed in the composites. Figure 8 shows that increasing the reinforcement content reduces wear loss monotonically while increasing hardness and ultimate tensile strength. This study discovered that adding reinforcement improves the wear resistance of aluminum composites significantly. These findings indicate that hybrid aluminum composites should be regarded as excellent materials where high strength, ultimate tensile strength, and wear resistance are critical, particularly in the aerospace and automotive engineering sectors.

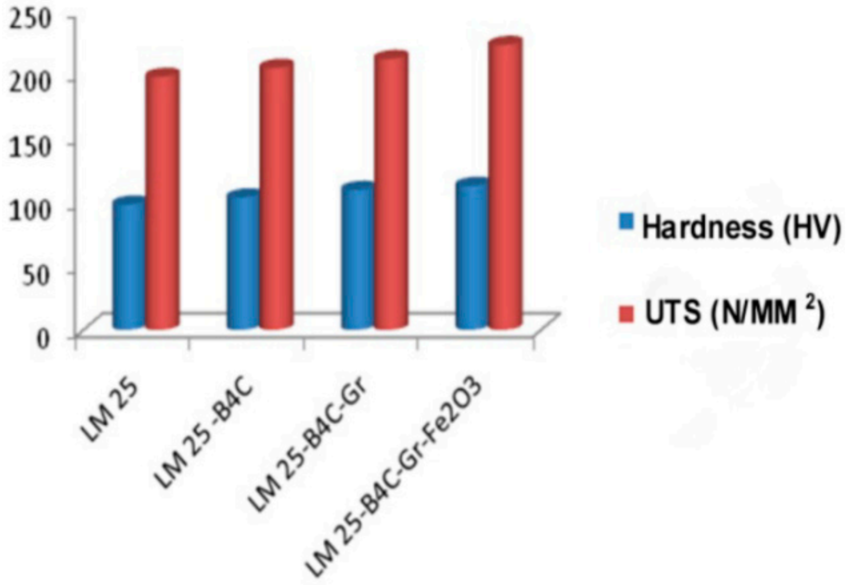

Figure 8. Variation of hardness and UTS of the samples [64].

Srinivasan et al. [65] examined the effect of graphite (3%wt) and zirconium oxide (ZrO_2) with changing weight percentage (2%, 4%, 6%) in AA6063 processed through stir casting technique. The micrograph's distribution of reinforcements shows that the stirring was successful. The reinforcements' clustering was reduced, and the blending of the reinforcements with the aluminum matrix was formed as a result of proper stirring. They revealed that addition of reinforcement particles increases the mechanical properties such as hardness and tensile strength. Several research studies about Al 6063/TiC proved that an increase in reinforcement weight percent increases the hardness and tensile strength [66]. This means that the statement is valid for composites with one or two reinforcements.

The current work on the stir casting process investigations of hybrid aluminum matrix composites was rigorously analyzed, and their findings are comprehensively described in Table 5.

Table 5. Research articles about stir casting process.

Year	Writers	Matrix	Reinforcement	Findings
2020 [61]	Yashpal et al.	Al6061	Bagasse ash (37 µm, 53 µm and 75 µm)	As the particle size of bagasse ash rose, the tensile strength, hardness, and impact strength decreased.
2019 [63]	Vijaybabu et al.	Al7075	B_4C constant (2%), and fly ash (2%, 4%, 6%)	The hardness, elongation, density, and tensile strength increased with the increase in fly ash content in the base alloy.
2019 [65]	Srinivasan et al.	AA6063	Graphite (3%wt), ZrO_2 (2%, 4%, 6%)	Addition of reinforcement particles increases the mechanical properties such as hardness and tensile strength.
2018 [64]	Suresh et al.	LM25	Boron carbide (B_4C), graphite (Gr) and iron oxide (Fe_3O_4)	Adding reinforcement improves the wear resistance and increases the hardness and UTS.
2018 [60]	Kumar et al.	Al7075	Graphite and varying TiC content (1–4 wt.%)	TiC and graphite-reinforced AHCs outperformed standard Al7075 in terms of hardness, tensile strength, and wear resistance.

2.2.2. Squeeze Casting

Squeeze casting is a hybrid metal processing technique that combines the benefits of casting and forging into a single operation. When combining casting and forging processes, squeeze casting can eliminate solidification defects such as shrinkage, gas entrapment, it can reduce porosity level, and perform cold shut while casting [67,68]. The most important advantages of the squeeze casting process are near net shape, good castability, removal of porosities, reduced material waste due to the absence of a gating system, high dimensional accuracy, and improved mechanical properties [69–71]. When compared to gravity die casting, squeeze casting produces better results in terms of high integrity, fine grain size, and superior mechanical properties [72]. Other benefits of squeeze casting due to increased mechanical properties are no shrinkage, no metal waste, and good castability of squeeze cast components [73,74]. The upper die is moving while the lower die is fixed. In the preheated, fixed-bottom die, the reinforced smelt is ejected to solidify. Pressure on the mold melt is applied to finish solidification. Mostly, the squeeze casting process is utilized to produce very precise and well-castable components. Figure 9 shows the setup of squeeze casting.

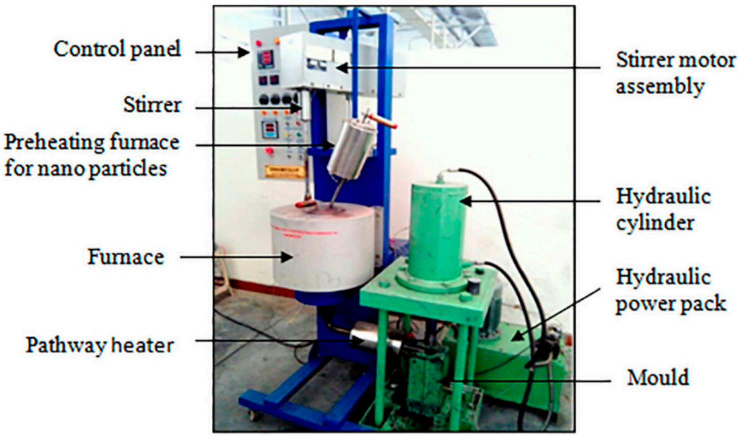

Figure 9. Squeeze casting setup [75].

Srinivasan et al. [75] fabricated AA6063 reinforced with zirconium oxide (ZrO_2) and graphite (C) by squeeze casting method by altering the weight percentage of ZrO_2 in steps of 0% up to 6% and keeping C as constant at 3%. They revealed that addition of ZrO_2 to aluminum hybrid MMCs reduces wear rate as the percentage of ZrO_2 added increases. With an increase in the transition load, the reinforcements minimize the wear rate. In comparison to the other compositions, wear in the AA6063/6% ZrO_2/3% C composition decreases as sliding speed increases. The wear resistance of AA6063/6% ZrO_2/3% C is greater. The fact that wear decreases as the sliding distance rises implies that the reinforced composite has favorable tribological behavior.

2.2.3. Centrifugal Casting

Centrifugal casting is a method of creating composites in which molten metal is fed into a spinning mold and the metals are pushed outwards to the mold surface by centrifugal force. In the most basic centrifugal casting methods, the centrifugal radial force produced during the rotation of the mold containing the melt transports and distributes secondary particles or phases from outer to inner in the radial direction with respect to the axis of rotation, in accordance with higher density to lower density compared to matrix density [76]. Figure 10 shows the basic functional diagram of centrifugal casting.

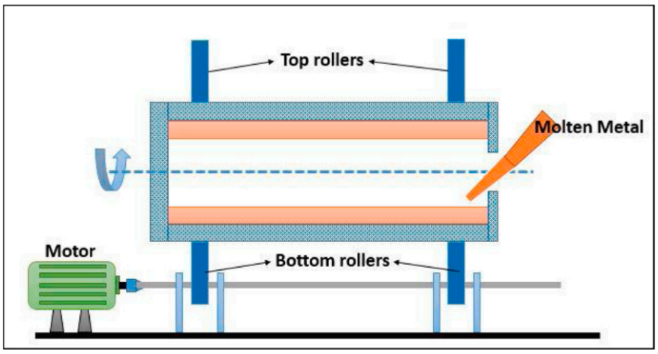

Figure 10. Centrifugal casting process [68].

2.2.4. Spontaneous Infiltration

The method of infiltration is carried out through a reinforcement phase and the melt is then inserted into this preform for the entire open porosity. In the systems where melt is moist, the reinforcement can only be caused by the capillary forces; otherwise, the resistance forces due to capillary drag and drag have to be overcome by a mechanical force. The pressure required when the matrix is combined with the strengthening depends on the friction effects because of the viscosity of the mold matrix, which fills the ceramic preform. Wetting ceramic preform with liquid alloy is dependent on various elements such as alloy content, preformed ceramic materials, and morphological surface, temperature, and time [40]. Table 6 summarizes some different techniques of liquid processing in HAMC manufacturing.

Table 6. The summary of liquid-state processing.

Manufacturing Method	Method	Influential Variables	Advantages
Stir Casting	The suitable reinforcement is added in molten metal at the melting temperature. Then, with the help of external device, the stirring process is carried out to distribute the reinforcement thoroughly throughout the molten metal to avoid the heterogeneous distribution and to reduce the porosity.	Applied load, sliding time, sliding velocity, sink size, stirring time, impeller capacity and size, molten metal temperature, melting duration, stirring speed, reinforcement type/size/%, melting rate, mold temperature, and heat treatment [28,56].	Large production, most effective, simple, low cost, flexible production [49].
Squeeze Casting	By using the closed die, metal undergoes solidification under pressure. Due to the movement of mold parts, pressure is applied over the molten metal, and it penetrates over the dispersed phase.	Stirring speed, squeeze pressure, pressure holding time [77].	Near net shape, good castability, removal of porosities, reduced material waste due to the absence of a gating system, high dimensional accuracy, and improved mechanical properties, Other benefits of squeeze casting are due to increased mechanical properties: no shrinkage, no metal waste, good castability of squeeze cast components, high weldability, high temperature resistance, good surface finish, high corrosion resistance, and high dimensional accuracy [49,73,74].
Centrifugal Casting	The process used is to combine comparable or different metal layers and fibers into sandwich metal at the required pressure.	Bonding temperature, pressure, holding duration, and surface roughness, temperature, pressure and the diffusion timing [49].	Controlling fiber orientation with metal volume fraction in various metal matrix composites.
Spontaneous Infiltration	The pressure-less infiltration process is another name for the spontaneous infiltration process. External pressure or forces are not used in this procedure when the liquid metal enters cavities.	Temperature and gaseous atmosphere [40].	Low cost, high precision with complexity in fabrication [40].

3. Properties of Hybrid Aluminum Composite

3.1. Physical Properties of HAMC

Density and Porosity

Ceramic reinforcements, in general, increase the density of the base alloy during composite fabrication. The insertion of lightweight reinforcements, on the other hand, reduces the density of the hybrid composites [78]. Several investigations of the density are described below.

Venugopal and Karikalan [79] observed that there is a correlation between the experimental and the theoretical density of the HAMC with the invention of reinforcement materials. Though TiO_2 has a lower density than matrix alloys (AA6061) and SiC reinforcements, the density of composites falls as a result of the SiC molecule and the fixed substance. It is due to the close proximity of high-density SiC particles that the density of the created composite is higher than that of the matrix material.

Alaneme et al. [80] researched Al–Mg–Si alloy matrix composites with aluminum (Al_2O_3) and rice husk ash manufacturing and mechanical behavior (RHA, an agro-waste). In preparation of Al–Mg–Si-alloy as 10% of the reinforcement phase as a matrix by two-step stir casting process, Al_2O_3 particles with added 0, 2, 3, and 4%wt RHA were used. The influence of RHA–Al_2O_3 %wt on composite densities was investigated using density measurements. In order to assess the porosity levels in the composites, the measured (experimental) density was employed. They noted that the low porosity levels discovered are a good indicator of the dependability of the hybrid composites two-step stir casting process. As the weight percent of RHA that makes up the reinforcement increases, the densities of the hybrid composites drop.

Boopathi et al. [81] evaluated the density experimental values for Al/SiC, Al/fly ash, and Al/SiC/fly ash composites. Because of the lower density of SiC, fly ash, and SiC–fly ash particles, the density of these composites decreased linearly. According to the findings, the interface between the matrix and the reinforcing particles is perfect. Similar results, in which density decreases as fly ash content increases, have been observed for fly ash-reinforced composites.

Rajmohan et al. [82] studied the influence of mica of aluminum matrix composites reinforced with 10 wt.% silicon carbide. The percentage of mica particles added was 0–6% in steps of 3% and a fixed 10 wt.% of SiC. The density of micro-reinforced hybrid composites that contain mica and SiC has been reported to be higher than the density of ceramic-reinforced composites. With increasing mica content, the density of the hybrid composite grew. The rise of density shows that the breakdown of particles may not alter composites significantly. The link between the particle and the matrix is supposed to be improved.

Porosity, especially in particles-reinforced MMC, has been acknowledged as a fault in strength enhancing. The cause of the production of porosity is air bubbles entering the material in the melting matrix, water vapor, gas interference when mixing, evolution of hydrogen, and shrinkage during solidification [83]. Because of the long particle feeding and the increase in surface area in contact with air, some porosity levels are normal during the fabrication of MMCs. In cast MMCs, the volume fraction of porosity, its size, and distribution all play a role in controlling mechanical properties. As a result, porosity levels must be kept to minimum, while porosity cannot be completely avoided during the casting process.

In aluminum alloys, interdendritic shrinkage occurs, which results in small, normally isolated gaps between the dendrite arms as a result of solidification shrinkage. It is also known as shrinkage porosity or micro-shrinkage. Fast cooling rates may alleviate this difficulty by allowing liquid to flow through the dendritic network to the solidifying solid interface since the dendrites will be shorter. Chvorinov's rule is used to calculate solidification time, shown in Equation (1) [84].

$$t_s = B\left(\frac{V}{A}\right)^n \tag{1}$$

where V symbolizes volume of the casting and represents the amount of heat, A is surface area of the casting in contact with the mold, n is constant (usually ~2), and B symbolizes mold constant, which depends on the properties and initial temperatures of both the metal and the mold.

By introducing the reinforcement particles to the matrix melt separately, the traditional stir casting method appears to increase the likelihood of gas entrapment and water vapor entry. Optimal MMC cast characteristics with less porosity content are achieved. In general, the rising porosity content reduces MMC's mechanical characteristics. Porosity reduces the mechanical characteristics of cast MMC by initiating the failing process from the vacuums.

Prasad et al. [85] manufactured aluminum composites reinforced in various volume fractions with 2, 4, 6, and 8 wt.% RHA and SiC particles According to the measured and theoretical densities, the porosity of aluminum alloy and hybrid composites increases as reinforcement increases, as illustrated in Figure 11. Gas entrapment during mixing, hydrogen evolution, shrinkage during solidification, and air bubbles entering the slurry either independently or as an air envelope to the reinforcing particles can all be blamed for the rise in porosity.

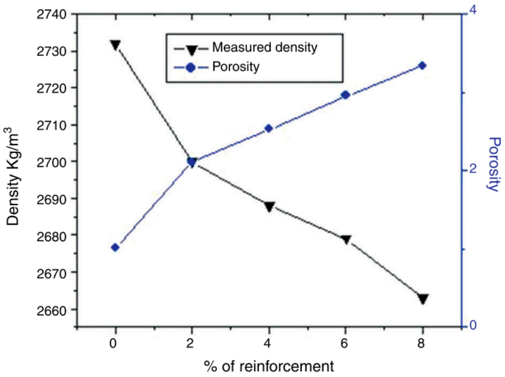

Figure 11. Variation in density and porosity with % wt of reinforcement [85].

Kumar et al. [79] investigated hybrid Al6061–tungsten carbide (WC)–graphite (Gr) MMCs. The composites were made using the liquid metallurgy technique, in which 0 to 4 wt.% of WC particulates were dispersed into the matrix alloy in 1 wt.% increases while keeping the Gr at 4 wt.% constant. The experimental results indicated that the density of the hybrid MMCs increases with increasing WC content. Optical and scanning electron micrographs of Al6061 alloy and Al6061–WC–Gr hybrid composites are shown in Figure 12. Micrographs show that the WC and Gr particulates are distributed fairly uniformly throughout the matrix alloy. Porosity was also found to be lower. Higher hardness is always associated with lower porosity of hybrid metal matrix composites, according to findings. Besides that, it can be seen from the optical and scanning electron micrographs that there is good bonding between the matrix and the reinforcement particulates, resulting in better load transfer from the matrix to the reinforcement material.

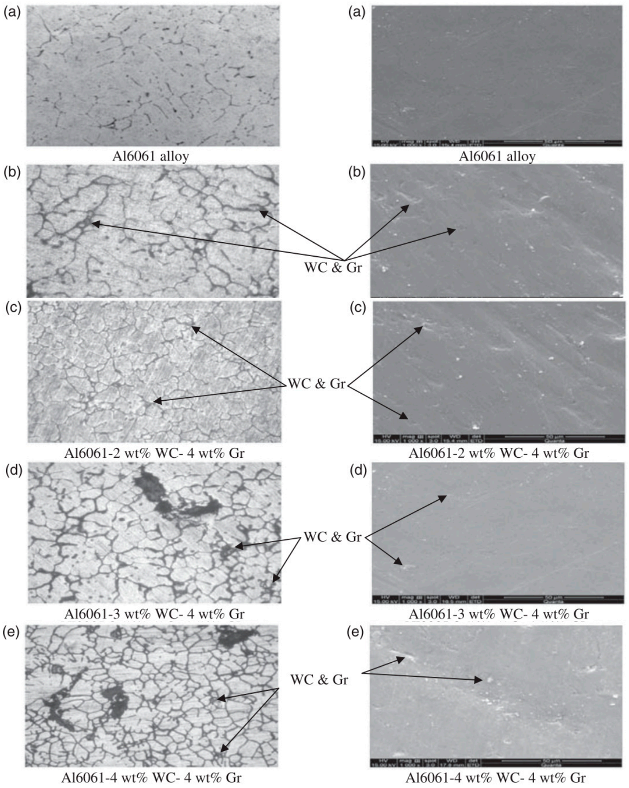

Figure 12. Optical micrographs of Al6061 alloy and its WC and Gr-reinforced HMMCs, (**a**) Al6061 alloy; (**b**) Al6061-1 wt.% WC-4 wt.% Gr; (**c**) Al6061-2 wt.% WC-4 wt.% Gr; (**d**) Al6061-3 wt.% WC-4 wt.% Gr; and (**e**) Al6061-4 wt.% WC-4 wt.% Gr [86].

According to some of the studies mentioned above, it can be concluded that the volume fraction and size of reinforcing particles play an important role in controlling the porosity level and physical properties of composites.

3.2. Mechanical Properties of HAMC

The mechanical properties of the composite are affected by the sintering temperature, reinforcement material weight percentage, and microstructure [87]. The addition of ceramic particles to the aluminum matrix improves mechanical properties [88]. The mechanical properties of MMCs are required to characterize the behavior of the composite material. Tensile strength, stiffness, hardness, and toughness were among the major mechanical qualities evaluated. These mechanical properties are critical in characterizing the behavior of composites. The mechanical properties of the hybrid aluminum nanocomposite were investigated by several researchers, as follows.

3.2.1. Yield Strength of HAMC

Several investigations of aluminum-based composites with yield strength were explored. Prasad [85] fabricated aluminum composites reinforced with various volume fractions of 2, 4, 6, and 8 wt.% RHA and SiC particulates in equal proportions. It was observed that the yield strength increases with an increase in the percent weight fraction of the reinforcement particles, whereas elongation decreases with the increase in reinforcement, as shown in Figure 13.

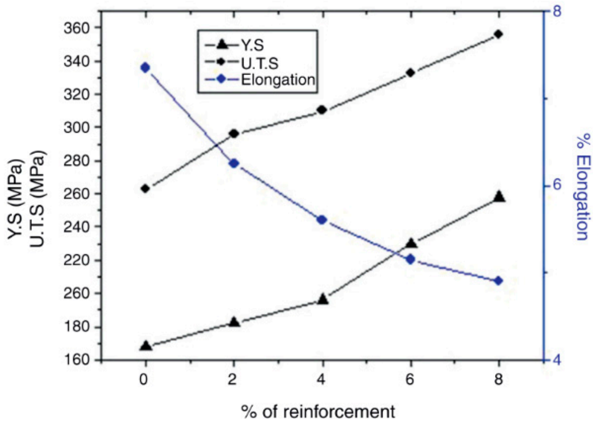

Figure 13. The effect of varying reinforcement on the yield strength [85].

3.2.2. Tensile Strength of HAMC

Tensile strength is a material's or structure's ability to endure loads that tend to elongate, as opposed to compressive strength, which withstands stresses that tend to reduce size [56]. Tensile testing is the most fundamental sort of mechanical test that may be performed on material. Tensile tests are easy, affordable, and completely standardized.

Venugopal and Karikalan [79] conducted tensile tests at room temperature (23 °C) using a universal testing machine (UTM) which was prepared according to ASTM E8M. Tensile strength was enhanced with increasing of content of SiC and TiO_2 particles in the composite, at the expanse of ductility. The tensile strength was increased by 280 MPa for AA6061/7.5% TiO_2/7.5 SiC, which was higher than the base materials. The inclusion of SiC and TiO_2 to the aluminum matrix improved the strength of the hybrid composites and reduced fracturing while the stress transformations for the corresponding displacements were performed. It is possible that the SiC on aluminum matrix contributed a significant role in the development of interfacial strength in metal matrix composites (MMCs) when compared to other constituents. The hard phases of particles SiC and TiO_2 facilitate strong interfacial strength where load transfer is adequate to produce the hybrid composites quality. As a result, increasing the volume fractions leads to an increase in the strength of the hybrid composites.

Baradeswaran and Perumal [89] investigated the influence of graphite on the wear behavior of Al 7075/Al_2O_3/5 wt.% graphite hybrid composite manufactured by stir casting method. It was found that increasing the weight % of reinforcing content improved the tensile strength of composites. Narasaraju and Raju [90] investigated the possibility of strengthening an aluminum alloy (AlSi10Mg) with locally available rice husk and fly ash to create a new composite material. Because of their low cost and great hardness, rice husk and fly ash could be used instead of SiC and Al_2O_3. Rice husk and fly ash have desirable characteristics such as high strength, extreme hardness, outstanding wear resistance, low coefficient of friction, high thermal conductivity, and great machinability. Using the stir casting method, hybrid rice husk and fly ash particles were introduced to the aluminum alloy matrix at 20% by weight in varying proportions. They also found a significant improvement in the mechanical properties of the hybrid composite. The optimum tensile strength was attained using 10% fly ash and 10% rice husk ash, which is identified as the best MMC in this work, as shown in Table 7.

Table 7. Results of tensile test of AlSi10Mg with rice husk and fly ash [90].

No	Sample Designation	UTS (MPa)
1	AlSi10Mg	350
2	AlSi10Mg + 15% fly ash + 5% rice husk ash	392
3	AlSi10Mg + 10% fly ash + 10% rice husk	410
4	Ash AlSi10Mg + 5% fly ash + 15% rice husk ash	386

Nathan et al. [91] fabricated HAMC using aluminum alloy 7075, and the varying weight percentage of reinforcements SiC of 2wt.%, 4wt.%, 6wt.%, and 3wt.% zirconium dioxide (ZrO_2) were taken for this proposed work. The AHMMCs were fabricated by the stir casting method at a melt temperature of about 740 °C and stirrer speed of 350 rpm for 5 min. The tensile strength of the samples improved as the weight % of SiC and ZrO_2 reinforcement increased, as shown in Figure 14, and it was more than the strength of the virgin matrix alloy. As a result, when the load is applied, the reinforcements function as dislocation barriers. By reinforcing the matrix, the hard reinforcement prevents the dislocation font. The greater property found was due to the alloys and reinforcements' strong bonding. The ratio for Al7075, SiC, and ZrO_2 on HAMC can be seen in Table 8. The sample 4 with (SiC 6%, ZrO_2 3%) 9% reinforcement had the highest tensile strength when compared to samples 1, 2, and 3. This is owing to the reinforcement particles serving as tensile stress resistance, as well as the strengthening mechanism via reinforcement load factor in the produced sample.

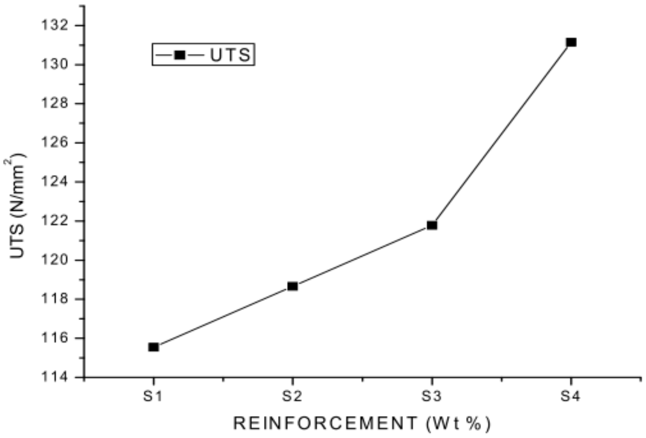

Figure 14. Tensile strength of Al7075–SiC–ZrO_2 composites [91].

Table 8. HAMC preparation ratio [91].

Sample Details	Al7075 (%)	SiC (%)	ZrO_2 (%)
S1	100	-	-
S2	95	2	3
S3	93	4	3
S4	91	6	3

B_4C and Al_2O_3-reinforced Al7075 matrix composites were prepared by Dhanalakshmi et al. [92] through stir casting method, and they observed increase in hardness and tensile strength of the composites with increase in the weight percentage of B_4C particulates in the aluminum matrix. This is consistent with the findings of Selvam et al. [93], who used SiC and fly ash as reinforcing materials and obtained similar results. The inclusion of SiC and fly ash particles in the matrix increases the strength of the matrix alloy by increasing its resistance to tensile stresses. This could be due to the reinforcement's strengthening mechanism via load transfer. The thermal mismatch between matrix and the reinforcement causes higher dislocation density in the matrix and load-bearing capacity of the hard particles, which subsequently increases the composite strength. Homogeneous particle distribution is a prerequisite for improving the mechanical properties of the matrix. Based on the results of the SEM micrograph, it is known that the FA and SiC particles are well bonded to the aluminum matrix, as shown in Figure 15.

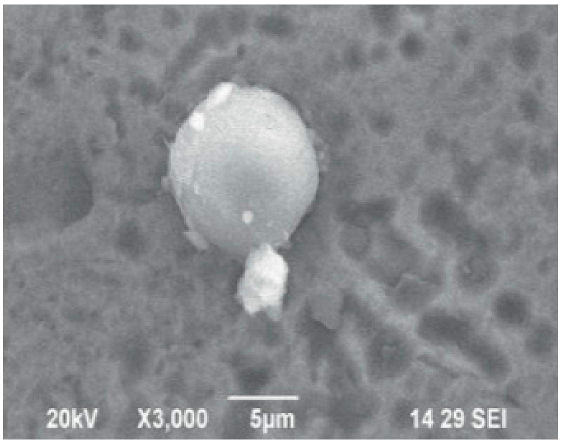

Figure 15. SEM micrographs of AA6061/fly ash compo cast composites containing 7.5 wt.% SiC–7.5 wt.% fly ash [93].

3.2.3. Hardness of HAMC

Hardness is the ability of the material to resist scratching or to withstand indentation. The ability of the substance to cut various metals is also defined. S. Venugopal and L. Karikalan [79] described the effects of different volume fractions TiO_2 and SiC composite specimen prepared in stir casting technique. The Brinell hardness (BHN) sample was tested at a weight of 250 kg. The graphical results show that the hardness of the MMC increase with increase in composition of TiO_2 and SiC (see Figure 16).

Pawar and Kharde [94] evaluated hardness of LM26 alloy and different hybrid composite prepared by varying weight fraction of Si and Ni–Gr. The composite hardness was found to increase as the reinforcement percentage increased, and the composite reinforced with 20%SiC had the highest hardness value.

Kumar et al. [95] carried out a study on mechanical behavior of aluminum matrix composite by analytical and experimental approach. In this aluminum alloy, Al356 + fly ash + Al_2O_3 was prepared by stir casting route. The hybrid reinforcement increased the hardness of composite material from 90BHN to 94 BHN, but the Al356 + 8%wt Al_2O_3

+ 8%wt fly ash hardness decreased due to the ASTM grain size being 8.95 µm. For 16% and 20% hybrid composite material, the hardness decreased due to porosity and strength.

Figure 16. The hardness of AA601 with TiO_2 and SiC as a reinforcement [79].

Suresha and Sridhara [96] found that the hardness of hybrid composites reinforced with SiC and graphite particles increased up to 2.5 wt.% reinforcement content (equal for both reinforcements) and then decreased (Figure 17). The increase was due to the addition of SiC particulates, while the decrease was due to the soft graphite particles' overriding effect. Because of the increased porosity levels, adding graphite particles lowers the hardness value. These findings suggest that the presence of ceramic particles improves the composites' resistance to indentation, while the presence of soft particulates, such as graphite, RHA, BLA, and others, reduces the composites' hardness value.

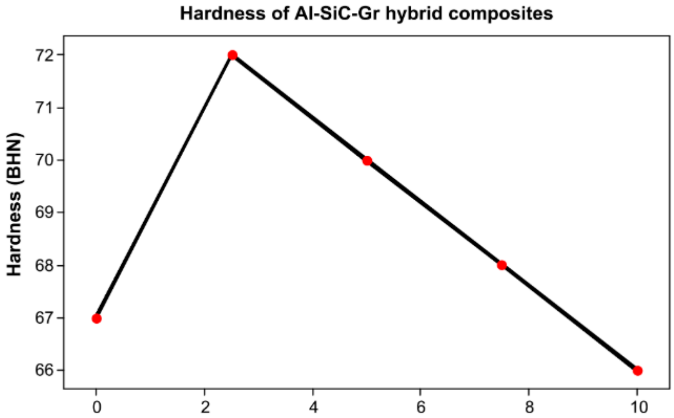

Figure 17. Effect of reinforcement content on Al–SiC–Gr hybrid composite hardness [96].

Mohanavel [97] investigated the mechanical properties of AA6351 composites reinforced with Al_2O_3 and Gr. The hardness of the AA6351 base matrix alloy increased as reinforcement increased. After the dispersion of Al_2O_3/Gr particles, the mechanical characteristics of the AA6351 alloy were greatly improved.

Dhanalakshmi et al. [92] investigated the influence of Al_2O_3/B_4C particles on microstructure and mechanical properties of AA7075/Al_2O_3/B_4C AMC which were fabricated through the liquid metallurgy route (stir casting method). In the mechanical characteristics of the composites, the influence of the mass percentage of reinforcing elements on the weight of Al_2O_3 varied by 3, 6, 9, 12, and 15 wt.%, while the B_4C weight percentage was constantly maintained (3%). With an increase in the weight percentage of the composites strengthened, the mechanical characteristics of the manufactured composites were improved. For a composite hybrid Al7075 matrix containing 15 wt.% Al and 3 wt.% B_4C, the maximum hardnesses of 140 VHN and 112 BHN, respectively, were attained.

James et al. [98] proposed a study on the characteristics of aluminum metal matrix composites reinforced with hybrid materials such as SiC and TiB_2. It is clear that combining TiB_2 with an aluminum matrix increases the hardness value. It has also been observed that as the percentage of TiB_2 increases up to 5%, the hardness value decreases abruptly. Cluster formation leads to porosity, which results in a decrease in hardness value. As a result of this experiment, we can deduce that a large number of reinforcements reduce the hardness of a metal matrix composite. Based on the results of the experiments, the optimal percent of TiB2 reinforcement is set at 2.5. James et al. also investigated the distribution's morphology using optical microscopy. The micrograph of clusters in the metal matrix, as well as the porosity, was caused by cluster formation. The SiC particles were surrounded by TiB_2 particles, which can be seen clearly in the micrograph. Interfacial bonding is not possible due to the lack of an aluminum metal matrix. This is due to the metal matrix phase's nonuniform reinforcement dispersion. The hardness of HAMC increased with increase in reinforcement content.

3.2.4. Ductility of HAMC

Ductility is the plastic deforming measure of the materials capability when placed under tensile strain, which exceeds, without division of, its production strength. The material is more suited for deformation and does not shake with high ductility. The structure, chemical composition of the components, and the temperature at which the ductility is tested are the key factors behind the ductility of the material in question.

Tang et al. [44] fabricated 6061 aluminum HAMCs with excellent mechanical properties reinforced with major SiC particles (SiCp) and stainless-steel particles with varying aging state. The aging of the temperature usually impacts the precipitation behavior of 6061 Al alloys [99]. The inclusion of stainless-steel particles increased the ductility of the hybrid-reinforced composites while maintaining their strength. When compared to the ductility of the Al matrix, the inclusion of SiC_p limits plastic deformation of the composites and significantly reduces ductility. The homogeneous strain distribution inside the hybrid composites was primarily responsible for the increased ductility.

Al6061–tungsten carbide (WC)–graphite (Gr) was also produced by Kumar et al. [86]. The composites were made utilizing the liquid metallurgical process whereby 0 to 4 wt.% of toilet particles were dispersed into the matrix alloy in 1 wt.% with the constant Gr of 4 wt.%. As a result, the ductility of the composites diminished monotonously and significantly as the proportion of WC increased. As the WC content dropped, the ductility fell from 1% to 4%. This is mainly because the composite becomes increasingly fragile, because the WC is more brittle than the matrix and Gr. As the WC content increased from 1 to 4 wt percent, the ductility declined by around 66 percent. This loss in ductility is more common in discontinuously enhanced MMCs in contrast to matrix alloys.

The stir casting technique was used to fabricate Al6061 reinforced with SiC and fly ash [100]. The experiment was carried out by varying the weight fraction of SiC (2.5%, 5%, 7.5%, 10%). The results show that elongation decreases with increasing particle weight percentage, indicating that the addition of silicon carbide and fly ash reduces ductility.

3.2.5. Toughness of HAMC

Ravesh and Garg [100] fabricated Al6061 reinforced with SiC and fly ash by stir casting technique. The experiment was conducted by varying weight fraction of SiC (2.5%, 5%, 7.5%, and 10%). The result indicated that increasing the weight fraction of reinforcement increased the toughness of Al/SiC/fly ash hybrid composites. This could be due to the matrix's proper dispersion of reinforcing particles or the reinforcement's strong interfacial bonding. The hybrid composite containing 10 wt.% SiC and 5 wt.% fly ash was found to have the highest toughness value in the study presented by the authors.

According to the above experimental work, several investigations of hybrid aluminum-based composites regarding mechanical properties were explored. Hence, the results show that mechanical properties such as ultimate tensile strength (UTS), yield strength, and hardness resulted in enhanced improved properties that were generated by increasing the reinforcing percentage compared to base alloy [101–104]. These findings suggest that the matrix material, size, and weight percent of reinforcements are important parameters that influence the mechanical properties of composites [20].

3.3. The Tribology Properties

Many papers have previously investigated the wear resistance of Al alloys supplemented with SiC in various forms (particles, whiskers, and fibers) and sizes. Furthermore, the tribological properties of these composites can be improved further by adding solid lubricant particles, such as graphite and molybdenum disulfide (MoS_2), to create hybrid composites [105].

Wear properties is one of the criteria to be considered for use in any engineering application, although many researchers are generally investigating the tribology characteristics of a range of aluminum alloys, whether in dry or wet conditions.

Baradeswaran and Perumal [106] investigated the wear characteristic of Al 7075/Al_2O_3/5 wt.% graphite hybrid composite using the stir casting method. It was concluded from the work that the wear rate of the hybrid composite decreases with the addition of Al_2O_3 and reaches a minimum at 2 wt.%/Al_2O_3/5 wt.% graphite, which is approximately 36% less than the wear rate of the matrix material Al7075, whereas the wear rate of the matrix material Al7075 increases with increasing sliding speed. The reduced wear rate of a graphite-containing hybrid composite can be attributed to the combined effects of graphite and Al_2O_3 particles in the creation of a more robust tribo-layer on the contact surface [107]. The graphite tribo-layer minimizes the amount of shear stress imparted to the sliding material under the sliding contact area, resulting in less plastic deformation in the subsurface region and a lower wear rate in hybrid composites.

Another work by Baradeswaran et al. [106] studied the aluminum alloy (AA) 6061 and 7075 reinforced with 10% boron carbide (B_4C) and 5% graphite using a liquid casting technique. The wear experiment was performed with a pin-on-disc apparatus with varied input parameters such as applied load (10, 20, and 30 N), sliding speed (0.6, 0.8, and 1.0 m/s), and sliding distance (1000, 1500, and 2000 m). The results reveal that adding 10 wt.% B4C and 5 wt.% graphite particles enhanced the wear resistance of the composites. RSM's graphical and analytical results revealed the best combination of applied load (10 N), sliding speed (0.8 m/s), and sliding distance (2000 m) for the lowest wear rate. When compared to the base matrix, the wear rate of composites was much lower. The MML generated on the composite's worn surface plays a critical function in determining the wear parameters of the composites.

Umanath et al. [108] explored the composite microstructure and the dry sliding wear behavior of AA6061/Al_2O_3/SiC AMC. The results revealed that the 15% hybrid composite wear resistance is superior to the 5% composite wear resistance. Low load, low rotating speed, and high counter-face hardness, combined with a high fraction in volumes, showed reduced wear. The volume fraction of the reinforcements was one of the other parameters that impacted wear. Dual tear ridges and cracked SiC and Al_2O_3 articles displayed a fracture surface, which indicates both the ductile and the fracture process. SEM images of the worn surface of reinforced Al alloy composites with 5% and 15% volume fractions are shown in Figure 18. On the worn surface of the composite alloy, there are cavities and large grooved regions. The ceramic particles found in the cavities include broken particles as well as particles pulled from the surface. The findings point to an abrasive wear mechanism caused by hard ceramic particles exposed on the worn surface and loose fragments between two surfaces. Wear resistance is higher in the case of composite alloy because the ceramic particles resist delamination.

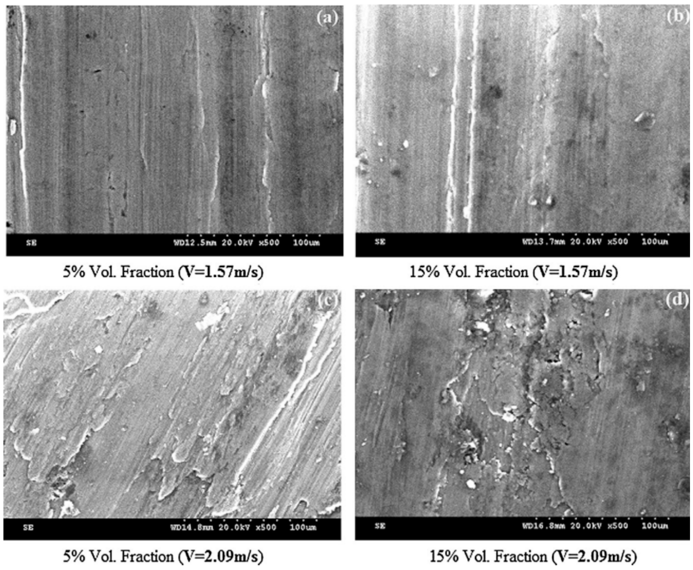

Figure 18. SEM photographs of the worn surface of different HMMCs. (**a**) Al/5% reinforcement composite at 1.57 m/s velocity, (**b**) Al/15% reinforcement composite at 1.57 m/s velocity, (**c**) Al/5% reinforcement composite at 2.09 m/s velocity, (**d**) Al/15% reinforcement composite at 2.09 m/s velocity [108].

From the several experiments, it was concluded that the wear resistance reduces with increasing of the percentage of reinforcement compared with base alloy [89,109,110]. This is due to the fact that the reinforcements minimize the wear rate as the transition load increases [77]. The increase in the content of reinforcements with base alloy improves the characteristics by raising the coefficient of friction [111].

4. Future Development and Application of Hybrid Aluminum Composite

The ubiquitous demand for affordable, efficient, and lightweight stiff materials has shifted research focus away from base alloys and toward composite materials in recent decades. Metal matrix composites (MMCs) are commonly used because they have an excellent combination of mechanical qualities. The development of hybrid aluminum metal matrix composites has grown, and some of the industrial application are discussed below.

4.1. Automotive

Aluminum alloys are commonly employed in the manufacture of lightweight automotive bodywork and parts. There are numerous techniques to obtain minimal weight without sacrificing strength or safety. It is usual practice to completely replace the present structural material with a material of better yield strength, with the possibility of reducing section dimensions. Another method for reducing weight is to replace traditional steel in specified sections with lighter materials. Because of its increased high-temperature properties, as well as its improved wear resistance, high strength, and fatigue life, HAMC offers a substantial application potential in car engineering [9], particularly for components such as pistons, car brake disks, connecting rods, engine, bearings, sprockets, and pulleys.

4.2. Aircraft

The characteristics of metal matrix composites suggest that these materials could be a viable option for further structural applications. Materials with uncommon combinations of properties are required for today's aircraft applications, which cannot be offered by ordinary metal alloys, ceramics, or polymers [112]. Low, yet sturdy, lightweight, hard, and impact-resistant properties are required for airplanes [112,113]. Wings, airplane chassis, and fuselage are examples of aircraft structures that use composites.

4.3. Rail Transport

Railway vehicles require durability and fuel efficiency for better load capacity [40]. Al6082, for example, is an Al–Mg–Si heat-treatable aluminum alloy with moderate strength, good weld ability, and corrosion resistance, as well as better process ability, and it has been widely used in rail transit parts [114]. Its strength, however, is insufficient for high-performance components. The strengthening of Al6082 is critical for expanding its uses.

4.4. Biomedical

AMCs have been considered for specialized application in which their combination of properties makes them especially well suited. Examples of these applications include medical and biomedical. These applications may require specific research and development activities to be carried out and technical problems solved before substantial use can occur. In medical technology, for example, mechanical qualities such as extreme corrosion resistance and low degradation, as well as biocompatibility, are important [115].

4.5. Building and Construction

Aluminum MMCs are useful for construction and building materials due to their strength and rigidity [116]. It is preferable to have durability, toughness, impact resistant, fatigue resistance, and corrosion resistance, which are often of primary importance for structural applications. HAMC can be used in the construction of bridge decks, fall protection, and as a shield against sunlight for buildings, window frames, door panels, and roof structures.

4.6. Sport and Recreations

Industry can produce lightweight sports goods with high strength by reinforcing them with silicon carbide or boron carbide. HAMCs used in the recreational markets, such as golf, baseball, tennis, bicycle tubing, track spikes, lacrosse stick shaft, and related products, are also manufactured with appropriate composition [49]. The brake surface of bicycle wheels is coated to improve wear resistance and reduce stopping distances. Because of the emphasis on performance over cost, recreational products have long provided profitable prospects for high-performance materials.

4.7. Electrical Transmission

HAMCs used in transmission have a high conductivity efficiency, a low thermal expansion coefficient, better strength, corrosion resistance, and are lightweight [117]. Superconductors, contacts, filaments, and electrodes are some of the components. These components are commonly used in telecommunications and radar systems for radio frequency (RF) microwave packaging. The lighter weight of Al/SiC is particularly advantageous for satellite microwave systems.

4.8. Packaging and Containerization

HAMC first arose as a distinct technology during a period when increased performance for advanced military systems was the driving force behind material development. The experience acquired in the designing and production of these numerous applications resulted in more extensive commercialization, one of which is in the food industry. Because of its high specific strength and stiffness, HAMC is used in the packaging of beverages, food container foils, and cold drinks cans in this industry [63].

4.9. Marine

Researchers in marine applications require a material which offers good specific strength and wear resistance [118]. Composite plays a vital role in modern material science, particularly in all types of transportation. Because of the lighter weight of the hybrid aluminum metal matrix composites, they are preferred for making fast-moving boats with aluminum coating for corrosion protection and superior weldability.

4.10. Defense

Researchers, particularly in the defense industry, are always on the lookout for materials that meet their specialized needs. Improving production procedures and locating substitute materials are two possibilities for meeting the aforesaid need [118]. Wings and related parts for airline, military, and helicopters are also manufactured. In tanks, aluminum–silicon carbide (whiskers) is used to withstand high temperatures [49].

5. The Challenges of HAMC Development

In general, the challenge of developing HAMC is to create a manufacturing technique that is both effective and efficient. The stir casting method is the most efficient for mass production, but this convenience is offset as the matrix has a poor distribution of nanoparticles and a high porosity. Fabrication of Al-matrix composites with alumina particles by casting is typically difficult due to alumina particle wettability and agglomeration phenomena, which result in nonuniform distribution and weak mechanical properties. Because of the poor wetting between matrix alloys and some reinforcements, manufacturing metal matrix composites is costly and difficult. The powder metallurgical method is the most capable of achieving good homogeneity, but it is difficult to apply to mass products and has relatively high production costs. Diffusion bonding is a relatively simple process that is highly productive and applicable to a wide range of situations, and the resulting joint material has uniform properties. As a result, the demand for composite materials processed using modern diffusion-bonding techniques has increased greatly. However, the difficulties and high cost of removing the oxide layer and maintaining a clean surface have limited the diffusion-bonding process's use in many industrial applications.

In terms of environmental concerns, the use of mineral waste, biowaste, and scrap as potential reinforcement materials for HAMC and its sustainability will require more attention. Further research on the HAMC with ceramic, biofiber, and industrial waste is required to improve the material's strength. Furthermore, the challenge of reducing the use of ceramic particles and oxides combined with natural reinforcing particles (sea sand) or waste (rice husk ash, bamboo leaf ash, red mud, fly ash) must be considered. Increasing the fraction of natural reinforcing particles and waste reinforcing particles will significantly reduce production costs while maintaining the expected mechanical properties. According to the above description, there are opportunities to develop HAMC based on specific manufacturing parameters to achieve the desired homogeneity, the effect of reducing the particle fraction of ceramic reinforcement and oxides, and the development of new reinforcement from industrial and agricultural wastes.

6. Conclusions

It is concluded that the various HAMC processing techniques have been thoroughly discussed, along with their advantages and disadvantages. Researchers will also have to find solutions to many challenges such as material cost comparison, development processing techniques, cost of reinforcement, process efficiency, the quality desired in the product, expenses of secondary processes such as machining or resizing, improved properties, and recycling of the products and wastes. The various HAMC processing methods and their properties were also discussed. The most recent advancements and applications of HAMC were detailed. HAMCs are increasingly used in industries, such as telecommunications, automotive, power semiconductor, military and aerospace, heavy transportation, space systems, medical, etc., because of their unique mechanical, physical, and tribological properties. In the future, there will be numerous methods for processing the HAMCs that we use for our applications and requirements. As there are many materials in the world, HAMC meets the requirements of low cost, simple production methods, and ease of application. There is a lot of room for newer manufacturing techniques to be used in the development of HAMCs in the automotive industry.

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