A Review of Synergetic Effects of Hybrid/Multiple Reinforcements on Aluminium Metal Matrix Composites

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Abstract

The development of aluminum metal matrix composites (AMMC) has been advanced in recent years. For advanced engineering materials, various scientists are seeking ways to improve matrix alloys through the utilization of reinforcements. Combining hybrid reinforcements over monolithic reinforcement in matrix alloy composite development has shown to be advantageous, since hybrid reinforcements complement each other in the matrix alloy. Production route of metal matrix composites (MMC) development is germane to improving their properties. This paper reviews the synergetic effects of hybrid reinforcements for AMMC on physical-mechanical properties and microstructure of the alloy. Various production routes were discussed, and the effects of utilizing hybrid reinforcement particulates were examined. Most studies employ stir casting route for MMC production, due to its ease of production and inexpensiveness. The study revealed that the utilization of hybrid reinforcements in MMC improves mechanical properties, with their even dispersion. Improvements in composites' strength are linked to three mechanisms: Hall-Petch, coefficient of thermal expansion and Orowan's strengthening mechanisms. Future research perspectives, such as novel processing techniques for MMC production, long-term performance and reliability examination on developed hybrid composites, were suggested to be further studied.

Keywords: advanced engineering materials; composite materials; hybrid reinforcement; mechanical engineering; metal matrix composites.

Introduction•

The advancement in metal matrix composites (MMC) in recent years has brought about spontaneous exploration of different materials to improve characteristics of the matrix alloy [1-3]. Composite materials are developed when two or more materials that show improved properties, when compared with their constituent components, are considered individually [4, 5]. Composites are lightweight materials that have applications for the advancement of engineering materials [6]. In MMC, matrix alloys could be Al, Mg, Cu, amongst many others. Numerous applications of aluminum

• The abbreviations list is in page 310.

metal matrix composites (AMMC) in real-life engineering applications and structures, such as automobiles, aerospace, marine, and sports, have led to attention being gained from researchers worldwide. Also, Al utilization in MMC development is due to their unique features or properties, which include low density, high strength, lighter weight, ease of machining, excellent malleability, good corrosion resistance, excellent thermal and electrical conductivity [7, 8].

In the same vein, MMCs contain reinforcements, which could include ceramic constituents and organic constituents [9]. Reinforcements are either synthetic reinforcements or ash made from industrial wastes or agricultural residues [4, 10]. The addition of reinforcement into a metal matrix to form composites can be done in a monolithic or hybrid way. When a single reinforcing particulate material is introduced into a metal matrix, a monolithic reinforced MMC is developed. However, the introduction of two or more reinforcing particulates into a matrix metal leads to the development of a hybrid reinforced MMC [1, 9]. Many materials scientists have extensively researched the utilization of hybrid or multiple reinforcements. However, in the development of AMMC, major technical challenges encountered that could make them expensive and complex are wettability, particle agglomeration, matrix interface bonding, and scattering [9]. These are being overcome by different novel production routes, such as double stir casting, powder metallurgy (PM) route, and combined stir and squeeze casting [11-13].

Several studies have utilized hybrid reinforcements in the production of AMMC [14-17]. As highlighted by [18, 19], hybrid reinforcements can be categorized as the usage of two or more synthetic reinforcements, a combination of a synthetic reinforcement and industrial wastes or agricultural residues, or the grouping of two or more industrial wastes or agricultural residues as reinforcements in a matrix alloy. The blend of these reinforcing particles could have different effects on the characteristics of Al matrix.

This review paper examines physical and mechanical properties, along with microstructure of hybrid reinforced AMMC, aiming to explore synergetic effects of using multiple reinforcements. The study considers various properties, including density, porosity, hardness, yield strength (YS), ultimate tensile strength (UTS), compressive strength, thermal and electrical properties, as well as fatigue and creep resistance. Additionally, the microstructure of developed composites and their fractured surfaces are analyzed. The discussion focuses on different strengthening mechanisms relevant to developed composites.

Brief overview of some production techniques

Various techniques have been employed for developing MMC, such as liquid-state, solid-state and deposition processes [19, 20]. One of these production routes can be utilized depending on required features for appropriateness and production cost reduction. AMMC are extensively reinforced for optimal results and performance in any industrial application. Processing parameters play crucial roles in analyzing appropriate mechanical properties.

Liquid state process

In this technique, a new composite is developed when the matrix, which is present in molten metal, joins forces with reinforcing particulates during liquid state production process. It combines the molten metallic matrix with ceramic reinforcements using liquid state route. After mixing and casting processes, various components are obtained for use in further production [9, 19]. Some of several liquid state processes that have been utilized for production of AMMC include stir, squeeze and spray casting [3, 21].

Of all these liquid state techniques, stir casting route is mostly used for developing MMC, as it is much simpler and less expensive. Stir-casting route ensures uniform dispersion of reinforcing particulates within the matrix alloy, which results in MMC's good wettability and reactivity [1, 18]. In this method, the matrix alloy is melted at about 750 ºC. Reinforcing particulates are preheated at 250 ºC to remove impurities and possible moisture. Hence, wettability of the reinforcement with the matrix alloy is improved. Preheated reinforcing particles are later introduced into the metal matrix at a molten state, being mechanically stirred at a speed range from 300 to 500 rpm, for about 10-15 min. This allows for uniform distribution of reinforcing particulates in the matrix alloy. Molten slurry is later poured into a prepared mold until solidification is achieved. Studies that have employed this method are numerous, including [22-26].

Another method under liquid state processing is squeeze casting method. This method is a high-speed method that helps to develop good surface finishes during MMC production. In this technique, matrix alloys in molten state are poured into the bottom die while solidification procedure of the melt is subjected to utmost pressure force. Pressure is applied for solidification and achievement of the desired size of MMC.

Mechanical properties are improved by controlling reinforcement distribution ability for continuous wettability in molten metal matrix without neglecting maximum pressure application. It is a method that combines close die forging with gravity die casting. It is suitable for any kind of reinforcement [9, 19]. Fig. 1 displays schematic diagram for some liquid-state processes, such as stir-casting and squeeze-casting techniques.

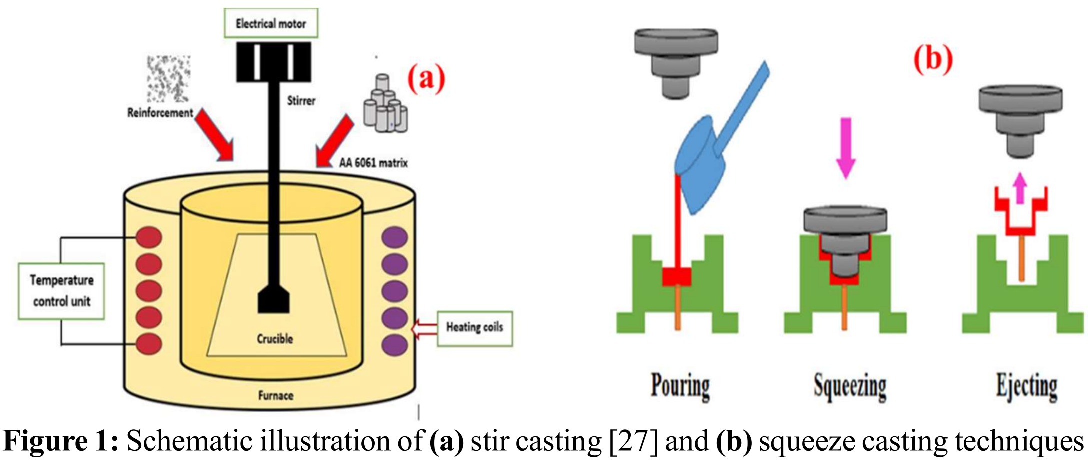


Figure 1: Schematic illustration of **(a)** stir casting [27] and **(b)** squeeze casting techniques [28].

Solid-state processing

Two major processes involved in production of MMC via solid-state route are PM and friction stir techniques. In PM route, metal powders are used for production of MMC with or without addition of reinforcements. This method involves powder manufacturing and preparation, proper mixing and compaction of powders (including reinforcements), and then sintering of compacted powder mixture to obtain the final product, as shown in Fig. 2a.

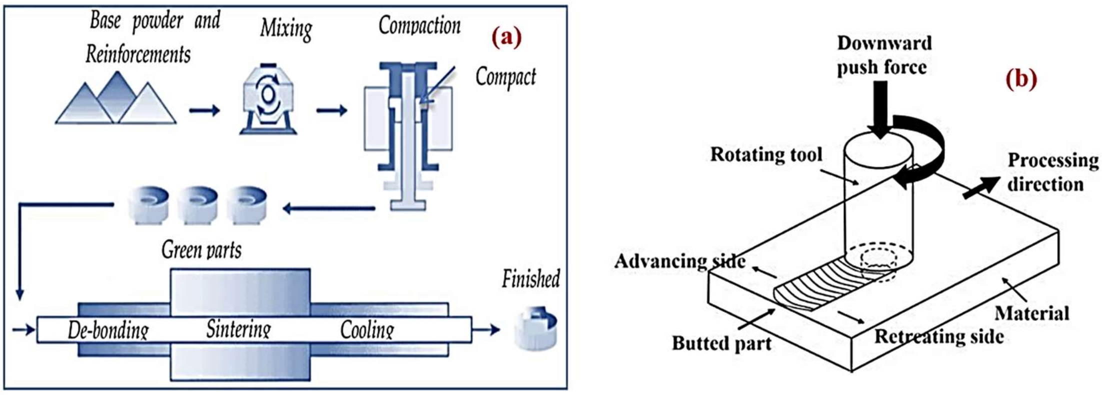


Figure 2: Schematic illustration of (a) PM technique [33] (b) Friction stir processing [34].

Sintering involves powder consolidation via compression at a high temperature to bring the matrix to its malleable condition [9, 19]. Like liquid state processes, PM helps to reduce porosity and poor wettability, thereby improving mechanical properties of MMC. Although PM is a viable processing route for MMC production, it is not appropriate for large-scale production. PM has been employed by [29] in synthesis of AMMC with reinforcement particles of SiC and alumina powders. Notable physical and mechanical properties enhancements were obtained compared to unreinforced pure Al. PM has also been used for AMMC development by [30], where Al6061 was the matrix, and reinforcements were SiC and B_4C. Mechanical properties of produced AMMC via PM route showed significant improvement. PM can be used to produce small round products like valves, bolts and pistons.

Friction stir processing (FSP) or technique is a thermomechanical process with the same mechanism as friction stir welding, as displayed in Fig. 2b. This technique helps to enhance microstructure and properties of the matrix. It is a surface engineering technique whereby characteristics of the surface are altered to achieve the needed target. FSP has been employed by [31] for production of AMMC using AA6061 as matrix alloy, with RHA as reinforcing particulates. Microstructure and tensile behavior of developed AMMC through the technique were investigated. It was observed that a homogenous distribution of rice husk ash particles was obtained, with no agglomeration or segregation in the matrix alloy. Tensile strength of reinforced AMMC showed improvement compared to unreinforced alloy. Excellent interfacial bonding with the matrix alloy was confirmed as a result of fracture surface dispersed with fractured RHA particles. In the study by [32], FSP was used in fabrication of AMMC. The matrix alloy was AA7075-T651, while coal fly ash and wood fly ash were used as reinforcements. FSP approach is expensive compared to PM, but it can be used for mass production of intricate structural elements [9].

Deposition process

The two major techniques in this method are compo- or rheo-casting and spray deposition approach.

Compo- or rheo-casting is an effective and efficient method for developing MMC. In this process, short fibers or preheated reinforcement particulates are introduced into a semi-solid and highly viscous molten metal slurry through agitation. This creates a phase known as pro-eutectic in the alloy slurry, which traps reinforcing particles and prevents segregation. A mutual matrix alloy-reinforcing particulate interaction is achieved through increased wettability and physical attraction between them through continuous stirring action of the slurry [9, 19].

In spray deposition technique, there is atomization of liquid metal melt into fine droplets via assistance of atomization gas that is introduced via nozzles. This leads to the deposition of a large number of fine droplets on a matrix alloy substrate present in the second part. Reinforcing particles in fine molten metal droplets are impacted by melted spray when atomized molten material droplets are pressed at a very high speed onto a preheated substrate, forming a composite [9, 19, 35].

This subsection highlighted various techniques for developing AMMC in solid and liquid states, and powdery form. All these processes have their pros and cons in ensuring that developed AMMCs maintain their mechanical, tribological and structural integrity when used. Generally, most commonly used fabrication technique is stir casting, which helps to distribute reinforcement particulates evenly in matrix alloy.

Reinforcement particulates in the development of AMMC

Before recent advancements in production of AMMC using different reinforcing materials, main reinforcing materials being used were referred to as ceramic-based or synthetic reinforcing particles. Although being costly, they are readily available and easily handled when developing composites [4, 21]. Some of these principal reinforcing particulates are SiC, Al_2O_3, B_4C, TiC, TiB_2, TiN and Si_3N_4. However, SiC and Al_2O_3 are majorly utilized reinforcement particulates in MMC development [18, 36]. Addition of these particles as reinforcements in the matrix alloy has been studied by several scientists to determine effects of reinforcements on properties of the matrix alloy. These studies have reported a good match between Al matrix and ceramic-based reinforcements [11, 26, 37-40]. It has been discovered that through good compatibility between matrix alloy and synthetic reinforcements, strong interfacial bonds are created in composites [41]. These reinforcements are initially used monolithically in

development of AMMC. With the advent of further research, many studies have employed two of these reinforcement particulates to form AMMC. Combination of these two or more reinforcing particulates was termed hybrid reinforced AMMC, which helps to mitigate difficulties encountered through use of monolithic synthetic reinforcement. The essence of hybrid reinforcements is for reinforcing particles to complement each other in AMMC for improvement of properties [16, 41-43].
For about a decade now, due to abundance of waste materials from agriculture and industries, these agricultural and industrial wastes have been utilized in development of AMMC. This helps with sustainability of environment [44]. Derivatives of these agricultural and industrial wastes in the form of ash contain chemical constituents such as SiO_2, Al_2O_3, Fe_2O_3, MgO, CaO, which are ceramic-like. They are hard and brittle materials that serve as strengtheners and hardeners in the matrix alloy when used as reinforcements [45]. A schematic illustration of reinforcement particulates is shown in Fig. 3.

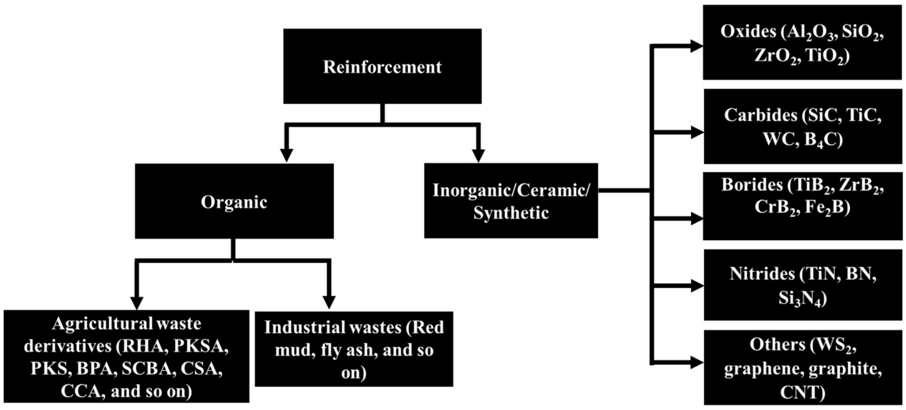


Figure 3: Schematic illustration of reinforcement categories.

Some derivatives of agricultural and industrial wastes that have been used are bean pod ash, cocoa pod ash, coconut shell ash, rice husk ash, corn cob ash, palm kernel shell, palm kernel shell as, fly ash, red mud, carbon nanotubes (CNT) and sawdust ash [13, 45 - 48]. Some of these agricultural and industrial wastes that have been utilized are presented in Fig. 4.

Figure 4: Agricultural and industrial wastes used as reinforcement in AMMC development.

Table 1 displays chemical constituents of some agricultural and industrial wastes, which make them useful as reinforcements in AMMC development.

Table 1: Chemical constituents of agricultural and industrial wastes.

S/No	Wastes derivative	Chemical constituents (wt.%)	Ref.
1	Coconut shell ash	SiO_2 (36-40), Al_2O_3 (23-25), Fe_2O_3 (11-16), CaO (3-5), MgO (2-3), K_2O (0.7-0.9)	[49]
2	Sawdust ash	SiO_2 (65.31), Al_2O_3 (6.08), Fe_2O_3 (3.27), CaO (9.98), MgO (5.78), K_2O (0.64), Na_2O (0.95), P_2O_5 (0.56), TiO_2 (0.99), MnO (0.01), SO_3 (2.85), LOI (3.60)	[47]
3	Palm kernel shell ash	SiO_2 (66.9), Al_2O_3 (6.46), Fe_2O_3 (5.72), CaO (5.52), MgO (3.14), Na_2O (0.17), P_2O_5 (3.78), TiO_2 (0.53), MnO (0.08)	[50]
4	Corncob ash	SiO_2 (77.1), Al_2O_3 (5.64), Fe_2O_3 (2.97), CaO (2.45), MgO (1.71), K_2O (3.81), Na_2O (0.49), TiO_2 (0.25), MnO (0.23)	[51]
5	Bamboo leaf ash	SiO_2 (76.2), Al_2O_3 (4.13), Fe_2O_3 (1.32), CaO (6.68), MgO (1.85), K_2O (5.62)	[23]
6	Sugar cane bagasse ash	SiO_2 (71.1), Al_2O_3 (1.8), Fe_2O_3 (1.28), CaO (4.02), MgO (4.96), K_2O (10.7), Na_2O (1.02), TiO_2 (0.11)	[41]
7	Palm kernel shell	SiO_2 (55.7), Al_2O_3 (9.43), Fe_2O_3 (3.32), CaO (11.2), MgO (4.85), K_2O (9.71), Na_2O (1.76), MnO (0.72)	[52]
8	Melon shell ash	SiO_2 (84.3), Al_2O_3 (3.54), Fe_2O_3 (1.3), CaO (2.11), MgO (0.37), K_2O (4.7), Na_2O (0.53), MnO (0.36)	[53]
9	Breadfruit shell ash	SiO_2 (15.45), Al_2O_3 (35.80), Fe_2O_3 (30.34), Cr_2O_3 (5.06), MgO (1.20), K_2O (0.52), Na_2O (0.45), ZrO_2 (0.05), MnO (0.22)	[54]
10	Fly ash	SiO_2 (58.4), Al_2O_3 (30.4), Fe_2O_3 (8.44), CaO (1.3), MgO (1.53), K_2O (1.98), Na_2O (1.0), TiO_2 (2.75), LOI (2.45)	[24]
11	Cardboard paper ash	SiO_2 (29.30), Al_2O_3 (2.68), Fe_2O_3 (1.76), CaO (50.78), MgO (0.87), K_2O (0.01), Na_2O (0.30), TiO_2 (0.01), MnO (0.23), P_2O_5 (0.67), SO_3 (0.52), LOI (2.50)	[1]
12	Groundnut shell ash	SiO_2 (17.6), Al_2O_3 (5.93), Fe_2O_3 (3.43), CaO (9.89), MgO (9.79), K_2O (18.3), Na_2O (4.85), TiO_2 (0.22), MnO (0.08)	[55]
13.	Carbonized eggshell	$CaCO_3$ (94.0), $MgCO_3$ (1.0), $Ca_3(PO_4)_2$ (1.0), organic matter (4%)	[56]

These derivatives, when used as reinforcements in AMMC development, are referred to as secondary or additional reinforcing materials. These additional or secondary reinforcing materials have been utilized in monolithic and hybrid ways with synthetic reinforcement. Addition of synthetic and secondary reinforcing particulates, as hybrid reinforcements in AMMC, has led to improvement in characteristics of the metal alloy, as reported by several studies [12, 17, 24, 57]. Aside from hybrid reinforcement using synthetic and secondary reinforcing particulates, the utilization of two or more of the latter is being researched by scientists to produce lightweight AMMC for engineering applications. Some hybrid reinforcements that have been used by various scientists are TiB and TiC, TiC and graphite, Al_2O_3 and graphite, ZrB_2 and TiB_2, B_4C and CNT, B_4C and RHA, and SiC with: Al_2O_3; graphene; graphite; CNT; B_4C; RHA; CCA; PKSA; FA; and GSA [29, 30, 39, 58-67]. For instance, the introduction of RHA and FA as reinforcement particulates in A356 alloy to develop AMMC has been done by [68]. Effects of RHA and FA hybrid reinforcements used in the matrix alloy were investigated. There was an improvement in tensile strength compared to the unreinforced alloy. Hybrid reinforcement particulates of TiC and CNT were used in development of AMMC. CNT content was constant at 0.5 wt.%, while TiC concentration varied from 0.5 to 2 wt.% during production of AMMC. Uniform dispersion of particles was reported with reinforcement content increment. Properties of AMMC were enhanced compared to the unreinforced alloy [62].

Hence, reinforcement particles in metal matrix composite development are germane, due to improved strength and mechanical integrity they provide to the matrix alloy. Implementation of agro-waste reinforcements has also caused improvement of strength in developed AMMC due to presence of strengtheners and hardeners in their chemical compositions. More agro-waste materials can be explored as reinforcement particles in AMMC development.

Synergetic effects of hybrid reinforcements on the physical properties of AMMC

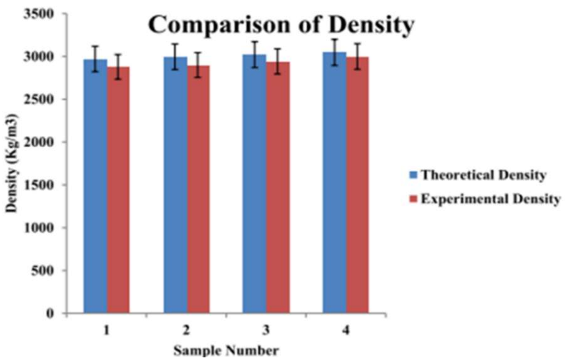
It is important to examine physical properties of developed AMMC with hybrid reinforcements to determine the influence of each reinforcement on the matrix alloy. In determining physical properties of AMMC, theoretical and experimental densities are important for evaluating porosity and its percentage. Theoretical density of composites is determined using rule of mixture principle, while experimental density of composites is evaluated using Archimedes' principle [69, 70]. Outcomes of theoretical and experimental densities are used to determine porosity of the composite by evaluating the difference between two densities. Theoretical density is always higher than experimental one.

Various studies have examined the impact of reinforcement particulates on physical properties of developed composites. Density (theoretical or experimental) of hybrid reinforced AMMC when FA and SiC are used as reinforcements has been studied by [24]. It was discovered that there was a reduction in densities of the composites, which was due to low density of FA in employed hybrid reinforcement. Percentage porosity was below 4% value recommended for cast MMC. Influence of hybrid reinforcement with quarry dust (QD) and alumina on physical properties of Al-Mg-Si alloy has been investigated by [17], using double stir-casting route. It has been reported that there was a slight increment in AMMC densities with rise in percentage weight of alumina in composites. The sample with 90% Al/2.5% QD/7.5% Al_2O_3 had lower densities compared to unreinforced alloy. However, the other samples had densities that were above the unreinforced alloy. This increase in density of the composite is linked with the rise in alumina weight over QD weight. Alumina possesses a higher density (3.95 g/cm^3) than QD (1.9 g/cm^3). Achieved porosities in the study were inferior to 3%, which is sufficiently lower than maximum permissible value of 4% in cast MMC. Densities of the composites produced in the study of [43] were found to reduce with the increase in volume fraction content of reinforcements in AA6082 matrix alloy produced via stir casting route. Density reduction of the sample with lowest density (AA6082/SiC/B_4C)

compared to unreinforced alloy was 5.2%. However, porosity has an inverse trend compared to density. Porosity of hybrid reinforced AMMC was about 2.14%. This implies that the stir-casting route is viable for producing advanced engineering materials with reduced porosity.

Theoretical and experimental densities of AMMC produced with Al6063/SiC/PKSA have been reported by [14] to slightly reduce compared to unreinforced alloy. However, both densities increased slightly more when SiC was used as a single reinforcement than those from PKSA. This was accrued to higher density and hard nature of SiC particles over those from PKSA in the matrix alloy. Combined effects of both reinforcements recorded decreased densities. It was observed that the percentage porosity of developed composites was below 2.2% without following any specific pattern. Porosity level could be influenced by trapped air and poor wettability of the reinforcement in the matrix alloy. Initiation of fracture is linked to the availability of pores, which could lead to stress concentration and eventual failure when subjected to loading [11, 12]. Homogeneous distribution of reinforcements in the matrix alloy via manufacturing techniques utilized is important for achieving porosity reduction below the required standard. For instance, [67] has established that major factors by which porosity can be controlled in AMMC development via PM route are high compaction pressure and sintering temperature. This implies that there is an establishment of good interfacial bonding between the matrix alloy and reinforcement particulates.

Four reinforcement particulates (Al_2O_3, RHA, WC, and SiC) as hybrid or multiple reinforcements in Al6061 matrix alloy for the development of AMMC have been employed by [71]. SiC content varied from 5 to 20% while percentages of other reinforcements were kept constant as follows: Al_2O_3 (3%), RHA (2%), and WC (2%). Two-step stir casting was the adopted production route for composite development. Amongst the experiments carried out were density and porosity. Theoretical density ranged from 2970.6 to 3047.1 kg/m^3, while experimental density varied between 2877.9 and 2999.2 kg/m^3. Porosity, which was obtained from the discrepancy between corresponding theoretical and experimental densities, ranged from 1.57 to 3.12% (Fig. 5).



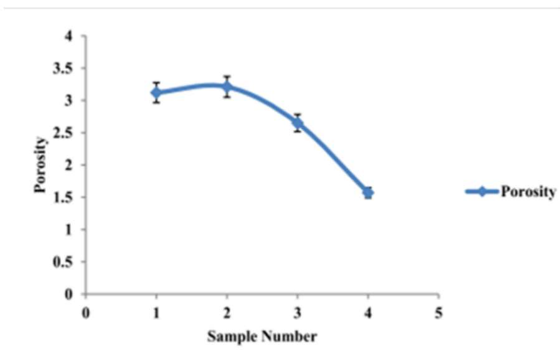


Figure 5: Density and porosity graph of Al6061/Al_2O_3/RHA/WC/SiC composites [71].

By observation, varied SiC content in developed composites leads to density increase with its higher content. Due to presence of voids, cracks and irregularities, experimental density was lower than theoretical density of the developed composite. Porosity of developed composites showed a declining trend with increase in SiC content, with a percentage value that is below 4% recommended for cast MMC. Achievement of this low porosity value was attributed to two-step stir casting technique used to enhance performance, such as increased hardness and impact energy.

Synergetic effects of hybrid reinforcements on mechanical properties of AMMC

Several scientists and researchers have employed two or more reinforcing particles as reinforcements in the aluminum matrix alloy, of which effects this sub-section considers. The effect of using hybrid reinforcement of B_4C, SiC and graphite on mechanical properties of AMMC made using AA7175 matrix has been investigated by [26]. Reinforcements' weight percentages in the matrix were 3, 6, 9 and 12%. AMMC development was done via stir casting technology. Hardness, tensile strength and percentage elongation were analyzed in the study. It was reported that hardness and tensile strength increased as reinforcement content decreased. However, percentage elongation reduced as reinforcement quantity increased. Hardness and tensile strength improved up to 12 wt.% of SiC, B_4C and graphite particles.

Stir casting technique was used to produce aluminum composites. Incorporated reinforcements in the matrix (AA2024) were B_4C (2, 4 and 6 wt.%) and graphite (2 wt.%). Afterwards, FSP was employed for grain structure enhancement and better distribution of reinforcements particulates in the cast product. Mechanical properties, such as tensile strength, hardness and fatigue, were tested on AMMC. Results revealed a homogeneous distribution of reinforcements through micrograph examination. Combined strategies of using hybrid reinforcing particulates from B_4C and Gr, as well as the use of FSP technique, improved hardness of MMC by 15% compared to unreinforced sample. Also, tensile strength of the composite improved by 69%. However, with a higher amount of reinforcement particulates in the composite, fatigue crack propagations increased [72].

Mechanical properties of Al6061 reinforced with fly ash (FA) and CNT particulates produced via stir casting route were investigated by [73]. Tensile, flexural, hardness and impact tests were conducted on produced AMMC. The control sample was Al6061/2% FA while other samples were Al/2% FA/0.2% CNT, Al/3% FA/0.2% CNT, and Al/4% FA/0.2% CNT. The study revealed improvement of hybrid reinforced AMMC compared to the control sample. Also, there was an improvement in flexural and hardness properties of hybrid-reinforced AMMC. However, it was reported that obtained values for the impact test were constant for all samples.

In the study by [24], mechanical properties of hybrid reinforced AMMC (Al-Zn/FA/SiC) produced via stir casting route were investigated on three samples were: A7075 (1), A7075/2.5% SiC/2.5% FA (2) and A7075/5% SiC/5% FA (3). It was observed that as reinforcement particulates increased in the matrix alloy, hardness values increased compared to unreinforced alloy. Hardness improvement was linked to the presence of hard chemical constituents of alumina and Si present in FA, as well as of SiC. Also, improved hardness values were linked to grain refinement of the matrix alloy. Hardness increased from 102 VHN (sample 1) to 120 and 125 VHN for samples 2 and 3, respectively. There was an improvement in YS and UTS of hybrid reinforced samples 2 and 3 compared to 1. Improvement in YS and UTS was due to the presence of hardest ceramic particles fused into the matrix alloy, of brittle and of hard constituents in FA particles.

Mechanical properties of stir-cast Al6063/SiC/PKSA hybrid composites have been evaluated by [12]. X-ray diffraction (XRD) phases revealed Al, SiO_2, Fe_3Si, MgO and SiC, which are considered to be hard brittle strengtheners for enhancing mechanical behavior. Mechanical properties (hardness, YS and UTS) of the composites enhanced as reinforcing particulates increased. Highest values of hardness, YS and UTS for hybrid reinforced composites (HRC) were 85.5 BHN, 102, and 133 MPa, respectively. Unreinforced alloy had 73 BHN, 79, and 116 MPa, respectively. However, a reduction of 34.2 and 40.11% was recorded for percentage elongation and fracture toughness, respectively. It was reported that SiC was a better strengthener as quantity increased in the matrix compared to PKSA in the reinforced composite. Generally, it was reported that mechanical properties of reinforced samples improved significantly compared to the unreinforced sample.

Two ceramic or synthetic reinforcing materials (Al_2O_3 and SiC) were used as hybrid reinforcement in production of AMMC. The matrix alloy was Al6061, and the production route was stir-casting. Aside from Al_2O_3 and SiC variation, a constant weight fraction of 5% FA was incorporated as the reinforcing particulates. Mechanical properties investigated showed improved high hardness, YS and UTS, and low wear rate. However, it was reported that impact strength showed no significant improvement in the samples [74].

The effect of TiO_2 and CuO nanoparticles addition to pure Al has been investigated by [75]. Nanoparticles were used as hybrid reinforcement in production of AMMC through PM route. Reinforcing particulates were examined using XRD, scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy. It was revealed that ceramic particles were uniformly distributed in the matrix alloy. Addition of TiO_2 and CuO reinforcing particulates yielded improved YS and hardness than those of unreinforced Al [75]. This implied that mechanical properties of the reinforced alloy improved due to synergetic effects of the reinforcement.

AMMC's mechanical properties, such as hardness, YS and UTS, were achieved using AA8011 matrix alloy and reinforced with ZrB_2 and Si_3N_4 particulates hybridization. Reinforcing particulates were found to be uniformly distributed in the MMC, and no visible porosity was observed. Mechanical properties of the developed hybrid reinforced AMMC revealed superior characteristics than those from the unreinforced

alloy. Mechanical properties of the sample with the highest content (20% ZrB_2-Si_3N_4) of reinforcements were better than those from the one with 5, 10 and 15 wt.% reinforcement [76].
Tensile behavior from HRC of AA6082/SiC/B_4C showed a rise in UTS with an wt.% increase in SiC and B_4C mixture reinforcement. This was credited to availability of a relatively good and homogenous distribution of the hybrid reinforcement. It was reported that all produced composites, as well as the unreinforced alloy, did not fracture at the middle of the sample's gauge length. However, they fractured at places where there was high stress concentration, due to the sample's continuous loading. UTS results varied from 381 (unreinforced sample) to 385 MPa (15% reinforcement), leading to an improvement of 21%. However, with 20% reinforcement addition to the matrix, UTS was lower than the one from the sample with 15% addition. This makes it the most superior AMMC developed in the study by [43].
By mechanical alloying and spark plasma sintering route, AMMC were produced using Al as a matrix, and reinforcing it with TiC and TiB_2 particulates (10, 20, 30 and 40%). There was a homogeneous dispersion of reinforcement particulates in the matrix alloy. Mechanical properties of the developed AMMC showed improvement with hybrid reinforcements compared to the unreinforced alloy. However, reinforcement optimum content for improvement of mechanical properties was found to be 20%. It yielded 135, 45, 195 and 194% for Vickers hardness, Young's modulus, YS and UTS, respectively. Mechanical properties of 30% and 40% reinforcement were lower than those from 20% reinforcement. The reduction could be due to an increase in the samples' porosity, and to dispersion of reinforcement particles in the matrix alloy. 20% reinforced sample had more uniform and more homogenous dispersion compared to 30% and 40% reinforced samples [37].
Table 2 presents some mechanical properties achieved by various researchers on AMMC hybrid reinforcements via different methods of production. Several studies have established three mechanisms that are linked to YS and UTS improvement for reinforced matrix alloys. These mechanisms are Hall-Petch effect, coefficient of thermal expansion (CTE) and Orowan's strengthening mechanisms [10, 25]. In addition, factors such as grain boundaries, substructures, solid solutions, a second phase significantly influence mechanical properties of hybrid reinforced AMMC [1, 54].
AA7075/RHA/B_4C hybrid composite produced via stir casting route has been examined by [77]. Mechanical properties of reinforced alloys improved compared to the unreinforced sample. The study has reported the presence of B_4C as the most influential parameter for improvement in hardness and tensile strength. The extent of refinement hybrid composites grains improved with the increase in RHA particulates. Clustering of reinforcement particulates resulting from particles agglomeration could lead to a weaker structure, while the presence of pores in developed HRC tended to lower UTS [43].
PM route was used to develop AMMC using Al with hybrid reinforcement of 7.5 and 15 wt.% SiC and Al_2O_3. Properties of the developed AMMC were compared with

those from the unreinforced alloy. Addition of these reinforcements increased the physico-mechanical properties of the reinforced composites [90].
In the study by [91], Al/Al_2O_3/SiC HRCs were developed via PM route. SiC content ranged from 0 to 8 wt.%, while Al_2O_3 was set at 5 wt.%. Physico-mechanical properties and microstructural examination of AMMC were investigated, having been reported that the increment in SiC content enhanced its physical and mechanical properties, due to homogenous distribution of reinforcement particles, as revealed by microstructural examination via SEM.

Table 2: Production methods and mechanical properties of hybrid reinforced Al-based composites.

S/No	Production method	Composite materials	Hardness	UTS (MPa)	Ref.
1.	Vacuum-assisted stir casting	Al6061/Al_2O_3/Bagasse ash	35 HV	150	[41]
2.	PM	Al6061/B_4C/BN	184 HV	248	[57]
3.	Stir casting	Al6061/SiC/TiB_2	135.56 HV	-	[78]
4.	Stir casting	Al6063/SiC/ZrO_3	95 BHN	382	[79]
5.	Double stir casting	A356/RHA/FA	95 BV	130	[68]
6.	PM	AA7075/SiC/Mn	97 HV	133	[42]
7.	Vacuum stir casting	Al-Mg-Zn/SiC/Al_2O_3	-	63	[80]
8.	Stir casting	Al7075/SiC/Gr	122 VHN	247.21	[81]
9.	FSP	Al7075/SiC/Al_2O_3/Ti/Eggshell	132 HV	-	[82]
10.	Stir casting	Al6063/TiB_2/Gr	60.63 HV	75.92	[83]
11.	Stir casting	Al6061/Al_2O_3/WSA	96.05	195	[84]
12.	Squeeze casting	AA2024/Al_2O_3/SiC	138 – 155 HV	390 – 450	[85]
13.	Stir casting	AA6082/SiC/B_4C	113 HV	387	[43]
14.	Stir casting	AA7475	113.03 HV	86.87	[86]
		AA7475/B_4C	138.60 HV	114.06	
		AA7475/TiB_2	127.50 HV	99.17	
		AA7475/TiB_2/B_4C	144.67 HV	156.57	
15.	Stir casting	LM25	55 HV	160	[87]
		LM/3 wt.% TiB_2/2 wt.% HEA	77 HV	230	
		LM/2 wt.% TiB_2/3 wt.% HEA	92 HV	255	
16.	Colloidal dispersion and suction filtration	Pure Al	32 HV	66	[88]
		Al/5 wt% SiC	44 HV	112	
		Al/5 wt% SiC/5 wt% C	90 HV	181	
		Al/5 wt% SiC/7 wt% C	104 HV	207	
		Al/5 wt% SiC/12 wt% C	150 HV	164	
17.	Stir casting	Al5083	83.02 BHN	162.9	[89]
		Al5083/0.6%B_4C	104.78 BHN	184.2	
		Al5083/0.3%ZrO_2/0.3%B_4C	125.21 BHN	215.1	
		Al5083/0.6%ZrO_2/0.6%B_4C	114.87 BHN	242.8	
		Al5083/0.9%ZrO_2/0.9%B_4C	122.87 BHN	197.4	
17.	Two-step stir casting	Al6061/3%Al_2O_3/2%RHA/2%WC/5%SiC	29 HRA	113.83	[71]
		Al6061/3%Al_2O_3/2%RHA/2%WC/10%SiC	30 HRA	118.33	
		Al6061/3%Al_2O_3/2%RHA/2%WC/15%SiC	33 HRA	120.00	
		Al6061/3%Al_2O_3/2%RHA/2%WC/20%SiC	35 HRA	130.15	

The influence of using FA and Al_2O_3 hybrid reinforcement on an Al matrix alloy developed via stir casting route has been examined by [92]. Synergetic effect of these particulates increased physico-mechanical properties of AMMC compared to single-reinforced FA composites.

With sugar cane bagasse ash (SCBA) and SiC as hybrid reinforcement in Al7075 alloy, [93] has developed a hybrid AMMC via stir casting route. The volume fraction of SCBA reinforcement particles was 3, 6 and 9%, and that of SiC was 3% SiC. Developed hybrid composites were compared with single-reinforced alloy (Al7075/SiC). The study reported that HRC with 3% SiC and SCBA had better economic and superior advantages over single reinforced and unreinforced samples. Hence, it was established that a hybrid reinforced composite, such as Al7075/SiC/SCBA, could be a better advanced material than single reinforced or unreinforced alloys. This composite would be important in applications requiring lightweight and mechanical properties enhancement.

Density reduction of composites is linked to the density of reinforcements used to attain light-weight status. Since density of aluminum alloy is higher than that from agro-waste derivative used as reinforcement, density of entire AMMC is reduced, which culminates in the production of lightweight composites. However, the strength of ceramic-reinforced AMMC is increased through prevention of dislocation movement [10, 25].

Generally, there is always a range of reinforcement weight percentages that are ideal for AMMC development. Most studies do not exceed 10 wt.% reinforcing particulate addition to a matrix alloy. Hybridization promotes a synergetic relationship between reinforcement particles and the alloy matrix. Hence, novel structural characteristics are witnessed with hybridization of reinforcement particles.

AMMC produced using Al6061 matrix alloy and reinforced with Al_2O_3 and WSA was characterized by [84]. Stir-casting route was used to develop hybrid reinforced composite. Alumina was kept constant at 5 wt.%, while WSA content was 1-3 wt.%. Microstructural examination revealed uniform dispersion of reinforcement particulates in developed samples. From mechanical properties analysis, it was reported that hardness and tensile strength of AMMC improved as reinforcement percentage increased. Improvement in hardness and tensile strength was 80.20 and 32.19%, respectively. However, elongation decreased with increased percentage content of ash in hybrid reinforcement used. Percentage reduction was 43.31%. Mechanical properties of AMMC showed significant improvement when compared with the unreinforced alloy. Increment in hardness and tensile strength values of AMMC was linked to decreased crystal grain size, matrix-reinforcement strong bond, reduced porosity level, and uniform distribution of reinforcement particulates. Improved mechanical properties were linked to load transfer from metal matrix alloy to reinforcement particulates. Reduction in elongation of reinforced composites with WSA weight fraction increase was due to the rise in the material's brittleness. These mechanical properties of reinforced AMMC were reported by several studies [10, 24, 94]. Hybrid-reinforced AMMC were developed using Al6061 as matrix alloy, while tungsten carbide (WC) and graphite served as reinforcing particulates through stir casting. Addition of Gr improved tribological properties of hybrid reinforced AMMC [66].

AA2024/Al_2O_3/SiC HRC was developed using squeeze casting method. Percentage reinforcement contents ranged from 0.5 to 5 wt.% in the metal matrix. There was uniform dispersion of reinforcement particulates in the matrix. Mechanical properties, such as tensile strength and hardness, increased with the increment in Al_2O_3 and SiC percentage weight [85].

Hardness values of some hybrid reinforced AMMC are displayed in Fig. 6. As earlier discussed, all HRC revealed superior hardness values compared to unreinforced composites. Hard nature of the reinforcement particulates introduced into the matrix alloy during development of hybrid reinforced AMMC is linked to observed improvements. Also, increment of the reinforcements in the matrix increases hardness values most times. However, at 12% SiC (Fig. 5d), it was discovered that there was a decline in hardness value. Increase to a certain level in reinforcement particulates in the matrix alloy could lead to agglomeration of particles, thereby lowering hardness of reinforced composites.

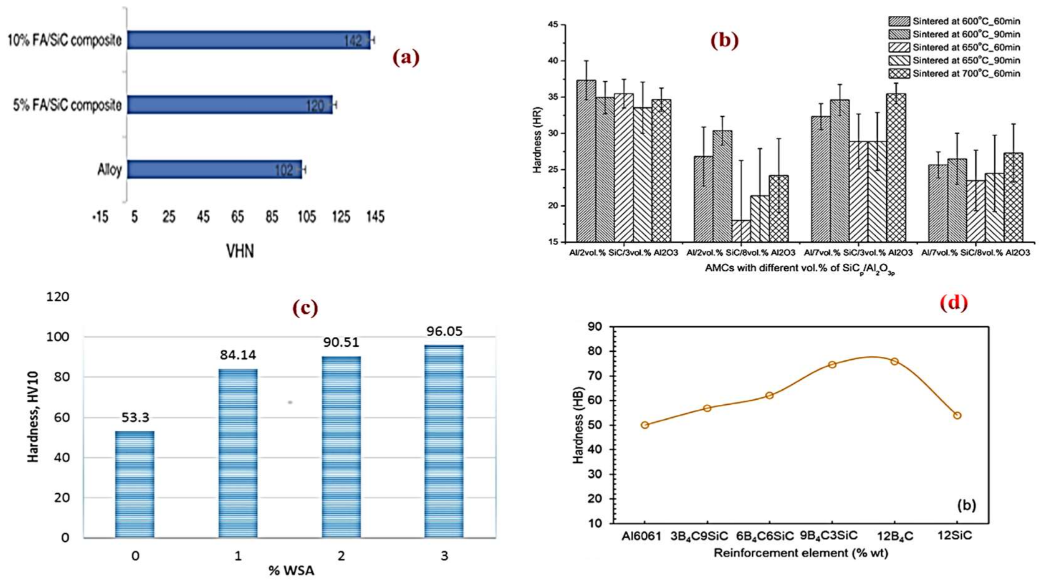


Figure 6: Hardness values with hybrid reinforcement content of **(a)** FA and SiC [24]; **(b)** FA and SiC [29]; **(c)** Al_2O_3 and WSA [84]; **(d)** B_4C and SiC [30].

Fig. 7 depicts the influence of hybrid reinforcement from different developed composites. Tensile strength of HRC was superior than that from single-reinforced composite or unreinforced alloy. Low CTE and good wettability match between the matrix alloy and the reinforcement are some of the reasons for tensile strength improvement.

An investigation of the influence of employing hybrid reinforcements from Al_2O_3 and Si_3N_4 in matrix alloy AA6061 for AMMC development was carried out by [95]. Composites were fabricated via stir-casting route. The effect of hybrid reinforcements on mechanical properties and microstructure of the matrix alloy was examined. It was reported that HRC outperformed single reinforced composite on tensile strength factores, such as UTS, YS and ductility. Dislocation density caused by availability of Si_3N_4 nanoparticles and appropriate bonding of hard particles from Al_2O_3 in the matrix alloy was reported to being the strengthening mechanism for recorded improvements. In the study by [96], when Al7075/B_4C/MoS_2 HRC were developed, mechanical properties (hardness, UTS, and YS) were assessed. Diffractometer evaluation showed presence of B_4C and MoS_2 in the developed HRC. Improvement mechanical properties of the developed composites compared to the unreinforced alloy was reported. The higher the percentage weight of B_4C and MoS_2 in the matrix alloy, the better the values of hardness, UTS and YS of the hybrid composite. The observed improvement was also linked to the reinforcements' harder particulates.

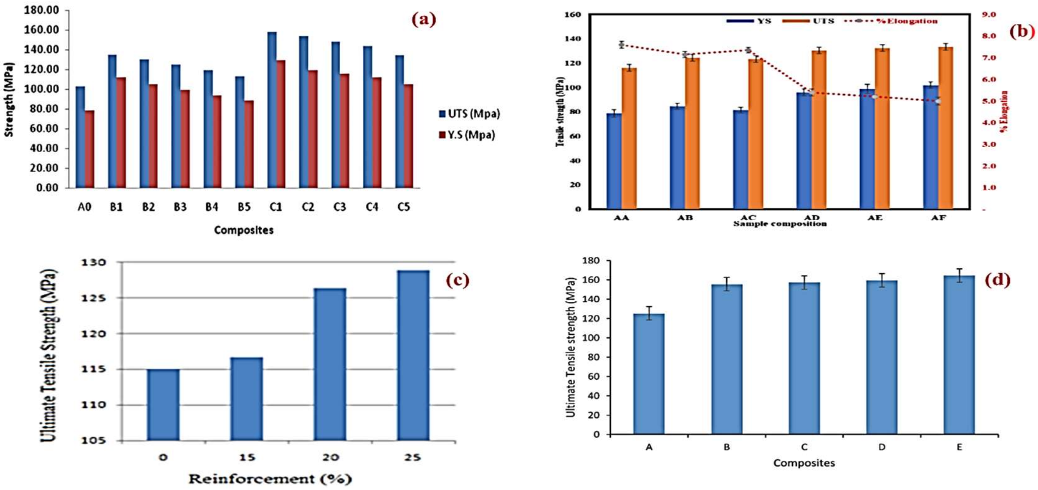


Figure 7: Tensile strength value with hybrid reinforcement content of **(a)** GSA and SiC [97]; **(b)** SiC and PKSA [14]; **(c)** SiC, Al_2O_3 and FA [74]; **(d)** Al_2O_3 and Quarry dust [17].

In situ TiB_2 and *ex-situ* B_4C have been integrated by [86] in the development of hybrid reinforced AMMC using AA7475 as matrix alloy. Production of the composites was achieved through stir-casting process before further characterization. Two single reinforced composites, using each of the reinforcements, were also produced for comparison, while maximum percentage weight of reinforcement particles in hybrid reinforced AMMC was 5 wt.%. The study revealed that HRC yielded superior values of hardness (144.67 HV) and tensile strength of 156.57 MPa. Synergetic effect of used hybrid reinforcements resulted in reported improvements. This assertion was due to lower values of hardness and tensile strength from AA7475/TiB_2 and AA7475/B_4C composites compared to HRC. The unreinforced alloy (AA7475) yields lowest mechanical properties in the study. It was asserted that produced hybrid composites could find applications in aviation, automotive and defense sectors, due to recorded improved properties.

A novel development method for actualizing high-performance MMC was performed by [98]. Microwave sintering was employed in the development of HRC using multiscale Al_2O_3 micro/nanoparticles (0, 2, 5, 8, 11, and 14 wt.%) and Fe-Co-Ni-Cr-Mn high-entropy alloy (HEA) particles (15 wt.%). The effect of hybrid reinforcements at different percentage weights of alumina micro/nanoparticles was investigated on mechanical properties. Also, strengthening mechanisms for recorded improvements were critically examined. Mechanical properties of single reinforced composites were worse than those from HRC. Orowan, thermal mismatch and dislocation strengthening mechanisms were critically linked to improvements in mechanical properties. Interfacial crack propagation was found to be delayed due to synergetic effects of hybrid reinforced particles from HEA and alumina.

In a similar study by [87], AMMC were produced using Al-Si-Mg alloy (LM25) reinforced with TiB_2 (*in situ*) and Co-Cr-Fe-Mn-Ni HEA *(ex-situ*), at 3 and 2 wt.%, respectively, via stir casting route. Duo reinforcements were reported to be evenly dispersed in the matrix alloy. The presence of both reinforcements was confirmed via diffractometric examination done on AMMC. Significant improvements were reported in mechanical properties of HRC compared to the unreinforced alloy. The composite LM25/2% TiB_2/3% HEA) had the highest tensile strength of about 255 MPa, followed by LM25/3%TiB_2/2% HEA mixture, around 230 MPa, while the unreinforced alloy (LM25) had about 160 MPa. This implied that the higher HEA content, the better the composite's tensile strength. The presence of hybrid reinforcements in the matrix alloy, as well as high dislocation density, was reported to have improved strength and ductility of hybrid reinforced MMC compared to the parent alloy.

Chicken eggshell, an industrial and aviculture waste, was carbonized to serve as reinforcement particulate along with SiC in the development of hybrid reinforced AA2024 MMC. The popular stir-casting route was employed in the development of AA2024/SiC/carbonized eggshell MMC with an addition of 1% magnesium powder to improve wettability and porosity reduction. In AA2024 matrix alloy, percentage weights of both reinforcing particulates ranged from 0 to 12 wt.%, with a stepwise increment of 3 wt.%. There was uniform dispersion of reinforcement particulates in the matrix alloy, which could lead to improved mechanical properties of hybrid reinforced MMC compared to the unreinforced alloy [56].

Synergetic effects of hybrid reinforcements from SiC particles and short carbon fibers have been applied by [88] on an Al matrix alloy. The composite was fabricated via colloidal dispersion and suction filtration technique. Dense-structured hybridized composites were obtained with evenly dispersed reinforcements in the parent alloy, which was responsible for high tensile strength and elastic modulus of HRC. Synergetic influence of hybrid reinforcements in the base alloy was reported and linked to improved mechanical properties of hybrid reinforced AMMC compared to single reinforced MMC. To fully establish a strengthening mechanism, a CTE experiment was carried out on samples, from 25 to 400 ºC. It was reported that CTE was lower for Al/SiC/C fibers composites compared to Al/SiC composites, due to addition of carbon fibers. Also, CTE of composites was lower than the one from the parent alloy. Average CTE of Al/SiC and Al/5% SiC/5% C fiber was 25.7 × 10^{-6}/°C and 22.7 × 10^{-6}/°C in a temperature range from 25 to 400 °C. Average CTE of HRC reduced with a rise in the volume fraction of carbon fibers. At 12 wt% carbon fiber content, CTE of HRC was 20.5 × 10^{-6}/°C. This CTE reduction of HRC was attributed to the mechanical limitation imposed by reinforcements (SiC particles and carbon fibers) on Al matrix's thermal expansion.

Mechanical properties of hybrid reinforced Al5083/ZrO_2/B_4C MMC, which were developed through stir-casting process, have been examined by [89]. Hybrid reinforced AMMC was compared with single (ZrO_2) reinforced composites at different percentage weights (0.6 – 1.8 wt.%) in the matrix alloy. For the same weight percentages, hybrid composites displayed better mechanical behaviors than those from ZrO_2 composites. Hardness, tensile and impact strengths of ZrO_2/B_4C reinforced composites showed improvement over ZrO_2 reinforced composites, with an increase in the content of reinforcements in the matrix alloy.

Mechanical properties of hybrid reinforced Al7075/B_4C/BN composites have been improved by [99]. The composite's development technique used was stirring-squeeze casting route. Weight percentage of B_4C was 3, 6 and 9 wt.%, and that of boron nitride (BN) was fixed at 3 wt.% for developing various composites. HRC displayed improved mechanical properties (hardness, tensile and compressive strengths), due to grain enrichments, evenly distributed reinforcements in the matrix alloy, and intermetallic phases generated in the composites.

Hybrid reinforcements of 3 wt.% BN and nano-SiC at 2 -6% were introduced into Al-Zn-Mg alloy to produce a composite via squeeze casting route [100]. The influence of these hybrid reinforcements on mechanical properties of developed hybrid composites was investigated. Hybrid composites showed significant improvement of 28.37, 32.53, 34.13, 31.25 and 27.27% in hardness, tensile strength, YS, flexural and impact strengths, respectively, compared to unreinforced Al-Zn-Mg alloy. Observed Improvements were due to wettability enhancement between hybrid reinforcement particulates and the matrix, and excellent grain refinement of composites. Morphological examination showed even dispersion of reinforcement particulates without residual pores, which could amount to improvemd composites' strength. A decline in dislocation movement was reported, due to the increase in reinforcement particulates proportion in composites.

AMMC with hybrid reinforcements of SiC (2, 3, 4, 5 and 6 wt.%) and B_4C (2 wt.%), and a SiC-reinforced composite have been developed by [101]. The method of developing composites was PM route and mechanical alloying process. Mechanical properties of single-reinforced and HRC developed samples were examined and comprehensively analyzed, which have significantly improved compared to the unreinforced sample. Presence of SiC particulates in single-reinforced composites revealed potential to improve mechanical properties of the composite. However, synergetic effects of SiC and

B_4C particulates in the matrix alloy greatly influence mechanical behavior of developed composites. Effects of hybridized reinforcements were significant compared to singly reinforced ones.

Composites comprising AA7178 as parent alloy, with TiO_2 and SiC as reinforcements, have been developed by [102]. Stir-casting route was used for developing composites to analyze the influence of reinforcements on mechanical properties. There was an improvement in tensile strength and hardness of developed HRC. However, ductility, which was obtained from percentage elongation, experienced a reduction with the increase in reinforcement content. Effects of using hybrid reinforcements on Al matrix alloy have been studied by [103]. By adopting dual-step stir casting method, Al6061 was used for developing composites. Hybrid reinforcement particles of submicron silicon nitride (Si_3N_4) and micron silicon carbide (SiC) were used in varying weight proportions and percentages. There was homogeneous dispersion of reinforcements in developed composites. Employed reinforcements were reported to be thermodynamically stable in the matrix alloy, since undesirable phases are not obtained in composites. Mechanical properties improved significantly compared to the unreinforced alloy, and maximum increase in hardness and UTS was 54.64 and 41.78%, respectively. However, not all hybrid composites showed significant improvements in ductility. Fracture mechanism of fractured composites was also established in the study.

Influence of premixed Al_2O_3 (μm) and Si_3N_4 (nm) metal powder as dual-size particle reinforcements in AA6061 matrix alloy on mechanical characteristics of developed composites was evaluated by [95]. Powders were first ball milled for 3 h, before being introduced into the matrix alloy, which was melted at 850 °C, and continuously stirred thereafter. Mechanical behaviours of composites were analyzed using appropriate protocols. HRC showed better mechanical properties than those from the unreinforced alloy. During development stage, Si_3N_4 nanoparticles were dominant compared to Al_2O_3 particles, which required the improvement obtained in dual reinforced composites compared to single reinforced composite or unreinforced alloy. YS, UTS and percentage elongation were respectively recorded as 67-148 MPa, 72.3-153.2 MPa and 2 – 8.3%, showing the effect of premixed Si_3N_4 nanoparticles and their percentage weight on developed composites.

A hybrid reinforced Al6061 matrix using MoS_2, SiC and B_4C as reinforcing particles has been developed and characterized by [104]. Reinforcing particles size varied from 3 to 12 wt.% in 3 wt.% steps. Synergetic effects of HRC were analyzed and showed mechanical properties improvements compared to the unreinforced alloy. Established strengthening phenomena were linked to improved properties of HRC. Similarly, mechanical properties of hybrid reinforced AMMC using Al_2O_3 (2, 4 and 6 wt.%) and 4% SiC as reinforcements in AA7075 alloy were studied. Reinforcements' average particle size from 35 to 40 μm was used, while composites were produced employing stir casting method. Uniform distribution of reinforcements in the matrix alloy was observed. High load-bearing capacity of reinforcement particulates from SiC and Al_2O_3 increased significantly compared to the unreinforced alloy [105]. Improvements in mechanical properties of composites are achieved due to synergetic influence of hybrid reinforcement particulates on the base alloy. These have been recorded by various scientists, and accompanying strengthening mechanisms have been discussed [78, 81].

In a recent development for environmental sustainability and waste recycling, [106] has utilized waste materials in the development of HRC. Materials used were waste aluminium, carbonized date palm fiber (CDPF) and spent alumina catalyst (SAC). SAC (6.25 – 1.25 wt.%) and CDPF (1.25 – 6.25 wt.%) were used as hybrid reinforcement particulates in waste aluminum, whereby balance weight percentage was from the base alloy. Composites were developed using stir-casting technique. Mechanical properties and tribological properties were evaluated. Addition of hybrid reinforcements significantly improved mechanical properties of composites compared to the unreinforced alloy. Increases of 21.84, 32.12 and 24.54% were recorded for tensile strength, microhardness and toughness, respectively. For tribological aspect, wear rate was optimally decreased with a reduced friction coefficient. Utilization of these wastes in development of AMMC would make the environment sustainable.

Compressive strength of AMMC

Compressive strength of MMC is a unique characteristic to be investigated for ascertaining area of utilization of produced composites. Compressive strength of AMMCs produced with SiC and B_4C particles as hybrid reinforcements in Al alloy showed significant improvement [101]. Synergetic effect of using SiC and B_4C as hybrid reinforcement showed significant compressive strength compared to monolithic SiC reinforced Al matrix composites. In the same vein, compressive strength of aluminium composites produced via stir-squeeze cast method with hybrid reinforcing particles from B_4C and BN was much higher than that from the unreinforced alloy [99]. Compressive strength of 956 MPa was attained for produced composites using an Al 7075 matrix with hybrid reinforced particles from Si_3N_4, TaC and Ti. Presence of the hybrid reinforcement provided a synergetic effect of enhancing compressive strength of the composite over the unreinforced alloy [107].

A cold compression test was carried out to evaluate compressive strength of AMMC developed using SiC and Al_2O_3 as reinforcements. Hybrid reinforced composite was produced via powder metallurgy route. Interestingly, compressive strength improved with an increase in hybrid reinforcements' volume fraction [29]. Higher compressive strength of AlSi10Mg reinforced with Cr_3C_2 and NiCr, and fabricated by selective laser melting, was recorded compared to pure AlSi10Mg. A typical shear fracture was obtainable as compression fracture with minimal plastic deformation [108]. The major cause of failure of composite materials during the compression test was discussed. When the direction of squeeze is parallel to shearing force direction, failure occurs.

For instance, after the reinforcement particle of Cr_3C_2 debonds under shearing force, debonding particles squeeze the matrix alloy (AlSi18Mg), causing an indentation.

Maximum compressive strength of 376.3 MPa was obtained with hybrid reinforcements of 10% Bagasse ash, 11% Aloe Vera ash and 10% SiC particles in Al6061 matrix alloy. Generally, synergetic effect of reinforcement particles improved mechanical properties, such as compressive strength of AMMC [109]. It can be deduced from some studies that synergetic action of two or more reinforcements significantly enhances mechanical properties of AMMC, including compressive and tensile strengths and hardness. Compressive strength is enhanced with increased reinforcement particulates within the matrix [110]. With higher TiN volume fraction in the Al7075 matrix, compressive strength was enhanced. The improvement was attributed to homogeneous distribution of TiN nanoparticles, resulting in limiting grain growth and dispersion strengthening [110, 111]. Vanadium carbide (VC), boron nitride (BN) and graphene nanoplates (GNPs) were employed in the fabrication of MMC. Three composites, i.e., AA7075/VC, AA7075/VC/BN and AA7075/VC/BN/GNPs, were produced. Compressive strength results of produced composites were compared to unreinforced AA7075 alloy. The unreinforced alloy and composites had compressive strengths of 411, 467, 492 and 519 MPa, respectively, for AA7075, AA7075/VC, AA7075/VC/BN and AA7075/VC/BN/GNPs. Compressive strength increased with addition of reinforcement particles, as displayed in Fig. 8. Enhancement was due to Orowan strengthening mechanism and Hall-Petch relation. This implies that uniform distribution of hard ceramic particles added to the matrix increased desired properties. Also, grain size refinement leads to increased grain boundary strengthening [112].

More studies are recommended to be carried out on compressive strength of hybrid reinforced AMMCs, especially that of synthetic reinforcements and agrowaste derivatives. This would help to establish a comprehensive mechanism to ascertain obtained enhancement.

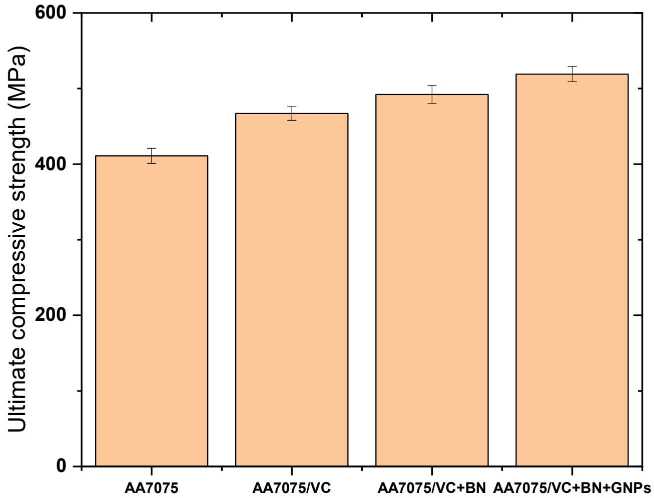


Figure 8: Ultimate compressive strength [112].

Thermal and electrical properties

Thermal behavior of MMCs is determined by variation in length of composites with temperature. Generally, length of all materials increased with higher temperatures for both unreinforced and reinforced composites. However, variation in length of the composites is lower than that of the unreinforced alloy [113, 114]. Thermal behaviour also depends on coefficient of thermal expansion of composites and Al matrix. There is usually a continuous increasing relationship between CTE of AMMC and unreinforced matrix and temperature. In the study by [113], a significantly lower CTE of Al reinforced with SiC particulates (SiC_p) and carbon fibers (C_{fs}) was observed compared to Al/SiC_p. CTE of Al-SiC_p was lower than that of the unreinforced matrix. Hence, with increasing volume fraction of carbon fibers, average CTE of Al/SiC_p-C_{fs} decreased. This reduction was linked to the mechanical constraint imposed by SiC particles and carbon fibers on thermal expansion of Al matrix.

According to [114], thermal expansions are restricted by reinforcement particles, such as SiC, Al_2O_3 and B_4C. Synergetic effect of hybrid reinforcement is more significant on CTE of MMC than of monolithic reinforced composites. In high-temperature applications, CTE enhances dimensional stability. A variation in thermal expansion of any composite is a major challenge in its development. However, thermal expansion properties may be controlled through proper distribution of particles or fibers in the matrix [114]. A typical thermal expansion behavior of unreinforced alloys and developed MMC is displayed in Fig. 9. There was a variation in length and CTE of the composites with an increase in volume fraction of reinforcement particles.

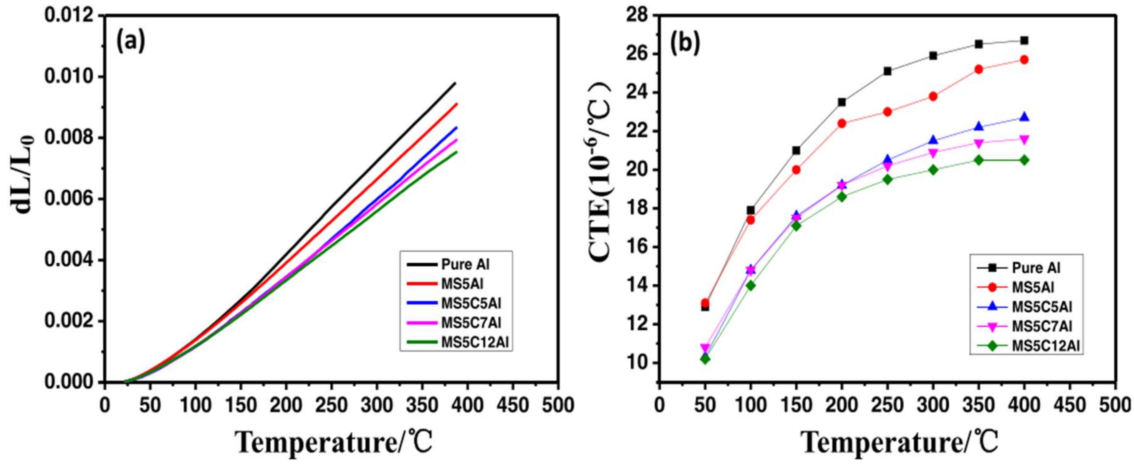


Figure 9: Thermal expansion behavior of Al alloy and Al MMC- **(a)** change in length vs. temperature curves; **(b)** mean CTE variation *vs.* temperature [113].

Electrical properties, including resistivity and conductivity, are important in employing AMMCs. Some studies conducted on electrical properties of AMMC are herein discussed. Alternating current (AC) conductivity of AA6063-T4 reinforced with different volume fractions (3, 5 and 7 wt%) of TiO_2 particles increased as volume fraction of the reinforcement increased with higher frequency. High AC conductivity of the composite was linked to induced polarization, i.e., interface-induced polarization and TiO_2 filler. Hence, dielectric properties and AC conductivity were enhanced [115]. Hybrid reinforcement of Al matrix with Fe_2O_3 and Al_2O_3 at 1.5 wt% and 2 wt%, respectively, showed improved electrical properties. Maximum conductivity was observed. Other studies also revealed that increasing reinforcement particles' volume fraction in a matrix would enhance AC electrical conductivity and dielectric properties [116,117]. Electrical conductivity of annealed fabricated composites reinforced with a hybrid of copper (Cu), tungsten carbide (WC) and molybdenum disulfide (MoS_2) showed enhancement [118].

When AA8011 alloy was reinforced with hybrid particles of ZrB_2 and Si_3N_4, it was reported that mechanical properties of the composites were enhanced. Also, increase in volume fraction of ceramic particles enhanced electrical resistivity of composites, while there was a drastic reduction in electrical conductivity [76], since resistivity and conductivity form a reciprocal relationship [13]. Increase and decrease in electrical resistivity and conductivity, respectively, are attributed to low conductive nature of reinforcement particles. Also, presence of porosity due to the fabrication route was a potential reason for the finding [111, 119, 120]. A similar occurrence of increasing resistivity and reducing conductivity was recorded when nanoparticles of Fe_3O_4 served as reinforcement in AMMC developed by [121]. Also, with use of PKSA nanoparticles as reinforcement in A356 alloy, electrical conductivity decreased with increased volume fraction of reinforcement particles. Meanwhile, electrical resistivity of composites was higher with increased volume fraction of the reinforcement. It was deduced that original crystallographic structure of A356 alloy, which was altered by PKSA nanoparticle reinforcement within the matrix alloy, could be responsible for this occurrence (Fig. 10).

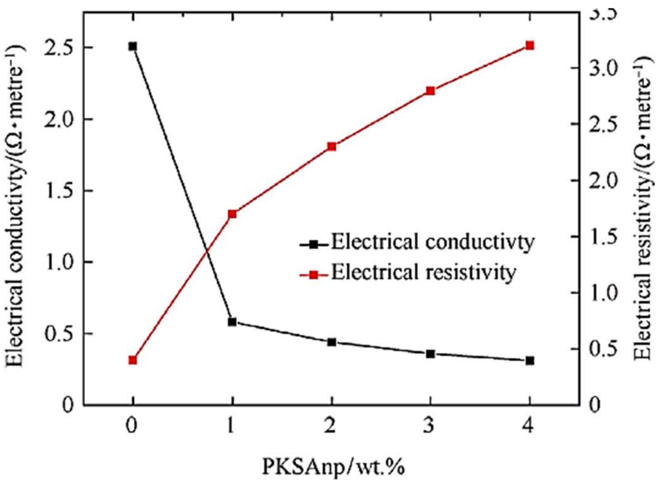


Figure 10: Electrical conductivity and resistivity of PKSA nanoparticles reinforced composites [13].

High electrical resistivity was linked to crystallographic arrangement disparity, which could have lowered electron mobility of the matrix [13].
More studies on thermal and electrical properties of MMC with hybrid reinforcements are needed to be conducted. Hybrid reinforced MMC with agrowaste derivatives, industrial wastes and ceramic reinforcements should be developed to evaluate their synergetic effects on thermal and electrical properties of the developed MMC.

Fatigue and creep resistance
Fatigue failures occur under conditions of dynamic, alternating and cyclic loading. These failures happen after an impressive time of service. Fatigue failure occurs at stresses well below the ones required for yielding, or above the yield strength, but not exceeding tensile strength of the material [122].
Hybrid reinforced AMMCs using ZrO_2 (6%) and Ni (6%) as reinforcement particulates has been produced by [123]. FSP was adopted as fabrication method with four different passes (1, 2, 4 and 6). It was reported that fatigue life of composites was extended with increased number of FSP passes (Fig. 11).

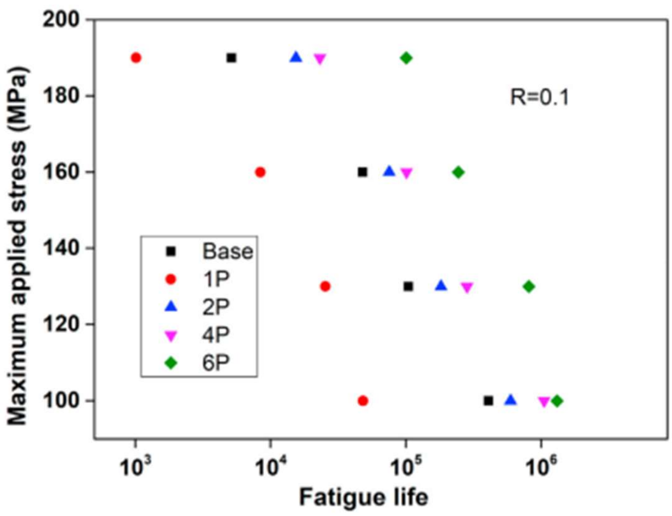


Figure 11: Graph of stress against fatigue life of Al matrix and HRC under various FSP passes [123].

Ductile-brittle failure mode characterized fatigue fracture of hybrid reinforced MMC with more than one FSP pass. Fatigue life span is affected by agglomeration or non-uniform distribution of reinforcing particles and by microstructural variability [124, 125]. It is decreased by local concentration of plastic deformation, due to clustering of reinforcement particles in the alloy matrix. However, it is enhanced when reinforcement particles are uniformly distributed due to improved load transfer. According to [126], fatigue life is enhanced by incorporation of reinforcing particulates in the Al matrix, which hinder crack propagation and reduce its rate. Also, compressive residual stress generation based on the fabrication technique adopted enhanced fatigue life [123]. Generally, rate of crack growth is slower in MMC compared to pure alloys. Higher stiffness of the composite results in enhanced fatigue curve behavior under controlled cyclic loads or high cyclic failure. For an improved fatigue behavior, selection of apposite reinforcement particle size and volume fraction within the matrix alloy is necessary. Fatigue resistance is enhanced when fine reinforcement particles are evenly dispersed in the matrix alloy [114].

Creep is a time-dependent deformation that occurs at elevated temperatures and constant stress. Temperature for creep initiation is dependent on the alloy composition [122]. Creep is reduced with reinforcement particles within a matrix alloy, leading to dislocation motion restriction. MMC reinforced with ceramic particles exhibit enhanced creep resistance compared to the unreinforced alloy [114]. Composites produced from Al5083 matrix and hybrid reinforcements (CNT and B_4C) showed improvement in creep resistance as reinforcement content increased. HRC have higher creep resistance than that from monolithic reinforced and unreinforced alloys [127, 128].

Studies on fatigue and creep resistance of hybrid reinforced MMC are scarce in literature. It is recommended that future studies are tailored towards these areas, to comprehensively explore enhancement phenomena of hybrid reinforced MMC over monolithic reinforced and unreinforced alloys.

Synergetic effects of hybrid reinforcements on microstructure of AMMC

It is important to perform morphological examination of hybrid reinforced AMMC for determining uniform distribution of reinforcement particles in the matrix alloy. It is also germane to examine pores or voids, and to view grain boundaries in the developed composite. Also, microstructural examination is carried out on fractured surfaces of composites after failure due to continuous tensile load. It is also employed to determine wear mechanisms on developed composites, after tribological experiments. Microstructures of developed composites are usually examined using optical microscope, SEM with an attachment of energy dispersive X-ray spectroscopy or transmission electron microscope (TEM) under different magnifications.

Factors such as reinforcement type, particle morphology and distribution in the matrix alloy greatly influence general behaviors or properties of the composites. Hence, even dispersion of these reinforcing particulates in the matrix alloy is germane. Achieving even distribution of reinforcement particles depends on the composites' rate of solidification, reinforcement type, melt fluidity, particle inclusion technique, reinforcement wettability in the matrix alloy, etc. [129, 130]. However, to improve wettability between matrix alloy and reinforcing particulates, magnesium is mostly employed [97]. Reinforcement particle distribution of hybrid reinforced Al6061/SiC/B_4C composites after development via PM route and vertical extrusion process was carried out by [30] using optical microscopy (OM). It was revealed that the unreinforced alloy had no pores, due to the material's high density occurring parallel to plastic deformation during extrusion process. Hybrid reinforced samples showed even distribution of particulates for samples with 3 wt.% B_4C content. However, agglomeration formation occurred with an increase in B_4C dosage. In 12 wt.% SiC composites, uniform distribution of the reinforcement was seen, while 12 wt.% B_4C showed a higher degree of agglomeration with limited pores in the micrograph (Fig. 12). A comprehensive microstructural analysis was carried out by [87], where OM, SEM and TEM were used. All equipment used for assessing the microstructure revealed homogenous distribution of hybrid reinforcements in the matrix alloy. For instance, OM revealed homogenous dispersion of flake-like silicon particles in the matrix, with evenly distributed HEA and TiB_2 particles. The unreinforced alloy (LM25) revealed a primary phase α-Al and Al-Si eutectic mixture. Also, homogeneous α-aluminum dendritic network structure for the base alloy was revealed by SEM. The structure was due to the sample's super-cooling when solidifying with a few numbers of contaminants present. There was an even distribution of reinforcement particulates from HEA and TiB_2 in the matrix, with heterogeneous grain size distribution. Also, there was continuous dynamic and geometric recrystallization occurrence between the matrix alloy and reinforcement phases. However, it was reported that, due to improved HEA content in the composite (LM25-2wt.%TiB_2-3wt.%HEA) and high-level dislocation densities, a finer structure was obtained compared to the composite (LM25-3wt.%TiB_2-2wt.%HEA). No pores were revealed in microstructures. Still, a small portion indicates the matrix-reinforcement interfacial regions, which significantly demonstrates no intermetallic phases brittleness at the interface. TEM also showed well-distributed reinforcement particulates in the matrix alloy, with no signs of intermetallic phases. TEM proved that there was no development of undesirable phases at the reinforcement-matrix interfaces. However, refined grain structure due to higher strength and higher dislocation densities, caused by HEA content increase in the matrix, makes LM25-2wt.%TiB_2-3wt.%HEA composite better than LM25-3wt.%TiB_2-2wt.%HEA.

In a composite developed using hybrid reinforcements of Al_2O_3 and HEA (Fe-Co-Ni-Cr-Mn) in Al matrix alloy, microstructural behavior of reinforcements in the matrix alloy was examined using SEM and TEM. It was revealed that both reinforcements were evenly dispersed at Al matrix grain boundaries rather than inside the grains. Interfacial wettability of HEA particulates was more easily linked to Al matrix grains. This resulted in elongated strips of particulates remaining at grain boundaries, which occurred when Al_2O_3 content was below 8%. However, with the increase in Al_2O_3, elongated long strips were transformed into small-sized particles. This could imply that grain boundary migration was inhibited by the rise in the Al_2O_3 content and the growth of Al and HEA grains [98]. There is a synergetic effect of the utilization of hybrid reinforcement, which culminates in improved mechanical properties of HRC. The processing technique and reinforcement types greatly influence the synergetic effects of the hybrid reinforcement, which could lead to the development of novel advanced engineering materials that would find applications in various engineering sectors.

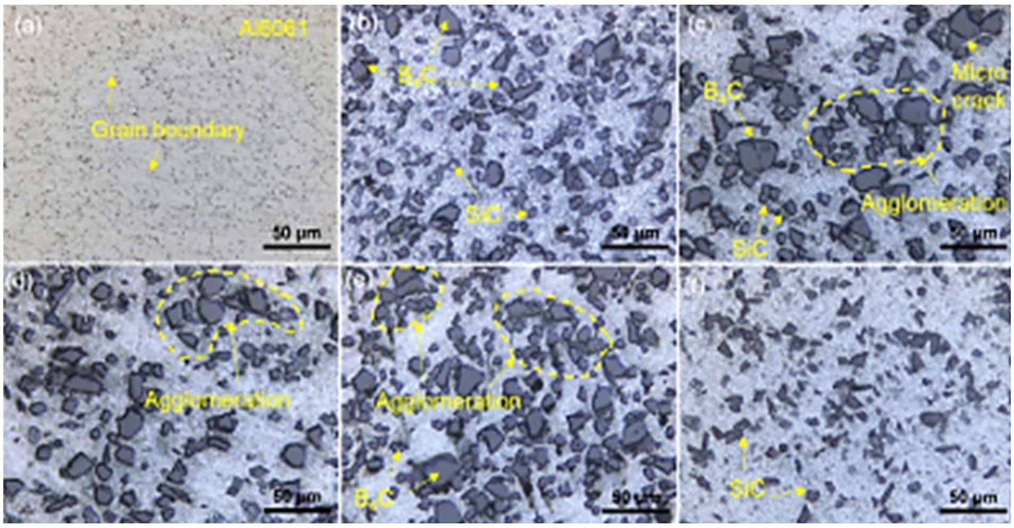


Figure 12: Optical microscope after extrusion of **(a)** Al6061; **(b)** Al/3%B_4C/9%SiC; **(c)** Al/6%B_4C/6%SiC; **(d)** Al/9%B_4C/3%SiC; **(e)** Al/12%B_4C; (f) Al/12%SiC [30].

Microstructural analysis of fractured surfaces is also important to establish strengthening mechanisms. For instance, SEM, in the study by [87], revealed several sheared or ruptured HEA particulates on the fracture surface of HRC. This occurrence leads to a load transfer from the matrix alloy to reinforcement particles, a fundamental phenomenon for strengthening MMC. Increase in HEA content for LM25-2wt.%TiB_2-3wt.% HEA composite led to the existence of more ruptured HEA in the micrograph, compared to LM25-3wt.%TiB_2-2wt.%HEA composites. Generally, numerous dimples of HEA reinforcing particulates were revealed. The fractured surface was not completely brittle, because of ductile dimpled rupture patterns. Therefore, load transfer mechanism from the matrix to the reinforcement phase is the primary strengthening mechanism. For load transfer mechanism to function in particle-reinforced composites, critical size of reinforcement particles must be below the point where they behave as dispersoids. Fig. 13 displays typical SEM illustration of synergetic effects from hybrid reinforcements on HRC's fractured surfaces. Synergetic influence of TiB_2 and B_4C as hybrid reinforcements in AA7475 alloy was determined on HRC's fractured surface compared to the single reinforced composite and the unreinforced alloy. Dimples observed on the fractured surface of AA7475 micrograph are few, which implies incomplete ductile fracture. SEM of the fractured surface of single reinforced composites (AA7475/B_4C), compared with AA7475/TiB_2 composite, reveals voidness, which results from B4C's poor wettability within the matrix alloy. AA7475/TiB_2 composite presented smaller voids with refined grains, supporting TiB_2 particles' grain refinement, which leads to ductility decline in the developed composite. However, fractured surface of HRC showed improved particle bonding with the matrix alloy, with no voidness, as revealed by the micrograph [86].

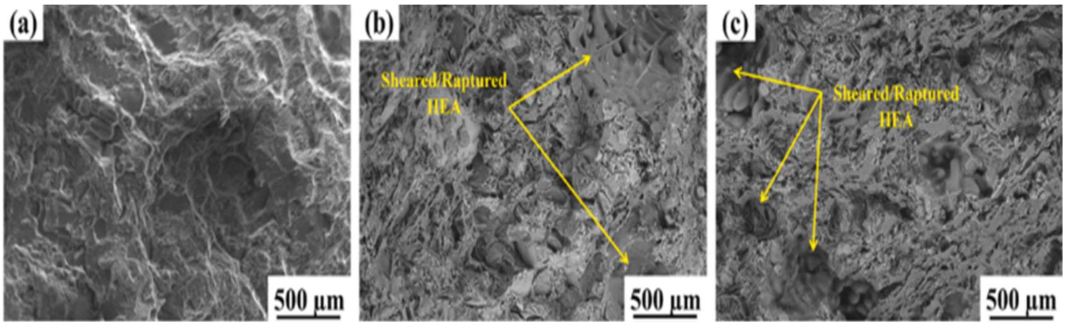


Figure 13: SEM fractographs of (a) Base alloy (LM25), (b) LM25-3wt.%TiB_2-2wt.%HEA, (c) LM25-2wt.%TiB_2-3wt.%HEA [87].

Morphological analysis has great importance for explaining underlying features and properties associated with mechanical characterization. In the study by [71], it was reported, through microstructural examination, that there was even dispersion of reinforcements in the matrix alloy, due to two-step stir casting method. This further explains enhancement of mechanical properties. Large craters were observed on the surfaces of developed composites. These were attributed to gas (air) bubbles that escaped during production method via two-step stir casting route, due to double rapid heating and cooling of the metal matrix. Also, it was reported that more the reinforcement particulates in the metal matrix, more the agglomeration that occurs. The presence of a crack was also observed, being linked to the presence of SiC's dendritic structure at higher concentrations. More nucleation sites occur with increased concentration of reinforcing particulates, which enhances crack propagation. This explains the relationship between concentration of reinforcement particles and crack formation. Furthermore, microstructural examination of the fractured surface revealed a tear structure. This points to a ductile fracture mode, which was confirmed by the existence of the dendrite structure and crack propagation. However, a smoother surface with fewer tears was reported for the fractured surface of composites with higher SiC concentration.

Applications of hybrid reinforced AMMC

Advanced engineering materials such as AMMC are important for various engineering applications, due to their high mechanical properties, low densities, excellent corrosion resistance, flexibility in design and manufacturing, tailorable properties, good tribological features and development of cost-effective products [21, 129, 130]. Several studies have established that AMMC are useful in aerospace, automobile, marine and sports industries, among others. For instance, composites have been the foremost materials preferred for lowering weight and fuel consumption with improved power train performance in automobile industry. Hybrid-reinforced AMMC are mostly used because of their low thermal expansion, high specific strength, excellent wear resistance and lightweight. They are used to produce braking systems, pistons, piston pins and rods, valve spring caps, brake pads and disks, etc. In aircraft, hybrid-reinforced AMMC have been used to develop gearboxes, turbine blades, wings, supporting tubes, among others [21, 37, 40, 131, 132]. This is due to weight reduction, reduced cycle time and part count, and manufacturing flexibility. This has led to higher range, fuel economy, fatigue, corrosion resistance and speed, due to reduced weight.

Future perspectives and research directions

Hybrid AMMC research area has witnessed significant advancement, due to increasing demand for advanced materials with enhanced mechanical properties for various engineering applications. These hybrid reinforcements have been shown to offer synergetic effects that significantly improve mechanical properties such as hardness, YS and UTS. Although much has been achieved in this regard, numerous other major areas are yet to be fully explored, which would require further extensive research exploration. Some future research perspectives are discussed in this section, which provide invaluable perspectives into MMC development.

One of the critical tasks in hybrid AMMC is accurately predicting synergetic effects of multiple reinforcements. Notwithstanding available empirical data, a holistic approach to fully understanding the interaction between various reinforcing particulates in a metal matrix still requires more attention. For future research, there should be more focus on the advancement of modeling techniques for accurate prediction of the mechanical behavior of hybrid composites under various loading conditions. Integration of machine learning to augment traditional modeling techniques could provide more accurate models for optimization of hybrid reinforcements in AMMC for tailored engineering applications.

Additionally, processing techniques used, such as casting, PM and additives manufacturing, have a significant impact on mechanical characteristics of AMMC. Manufacturing processes become even more difficult when several reinforcements are added to hybrid composites. Final qualities, for instance, are influenced by reinforcements' distribution, wettability of the matrix and reinforcements, and interactions between reinforcements. To improve control over dispersion and bonding of numerous reinforcements, future research should focus on improving current processing techniques and creating new ones, such as *in situ* synthesis, combining two or more processing techniques. This would also assist in improving mechanical properties of AMMC.

Furthermore, more studies should be done on long-term performance and reliability of hybrid-reinforced AMMC, which could include high-temperature, damping, corrosion-wear and -erosion tests, accelerated aging, fatigue performance, etc, especially in severe environments, including aerospace and automotive applications. Synergetic influence between different reinforcements on the matrix alloy reveals a better combined effect than individually using the reinforcement, which is a great advantage in MMC development. However, there are still latent areas about mechanisms required to fully understand these interactions between reinforcements. Hence, research should be done on further investigating the interactive mechanism between matrix alloys and reinforcement particulates, for a correct reinforcement optimization to obtain improved mechanical characteristics.

Conclusion

Hybrid AMMC represent a promising class of materials capable of meeting demanding performance requirements of various industries. Incorporation of hybrid reinforcement particulates in a matrix alloy during development of AMMC has led to improvement of mechanical properties from produced HRC. There is always a synergetic role of both reinforcements, where one strength tends to complement the weakness of the other, thereby improving mechanical properties. Influence of processing techniques during AMMC production is germane. A well-processed MMC could lead to homogenous dispersion of reinforcement particulates in the matrix and enhancement of grain refinement. With numerous considerable achievements and advancements in the field of advanced engineering materials, with regard to hybrid reinforcements and their synergetic effects on the matrix alloy, there is still room for further innovative research in this field, in order to improve properties of MMC. Such areas for further research could include, but are not limited to, modeling and optimization of reinforcement parameters, novel processing methods, reinforcement development, long-term performance analysis and sustainability. Addressing these challenges and exploring suggested future research tips could lead to realization of hybrid AMMC' optimum potential. Hence, ways are paved for next-generation materials that would possess excellent performance across a wide range of applications.

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Competing of interest

The author declares that there is no conflict of interest.

Author's tasks

Peter Pelumi Ikubanni: Conceptualization; methodology; writing, review and editing.

Abbreviations

AMMC: aluminum metal matrix composites
CNT: carbon nanotubes
CTE: coefficient of thermal expansion
FSP: friction stir process
HEA: high-entropy alloy
HRC: hybrid reinforced composites
MMC: metal matrix composites
PKSA: palm kernel shell ash
PM: powder metallurgy
SEM: scanning electron microscopy
TEM: Transmission electron microscopy
UTS: ultimate tensile strength
WSA: walnut shell ash
YS: yield strength

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