A critical review on hybrid aluminum metal matrix composite

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Abstract. The hybrid composites of aluminum metal matrix (AMM) are gaining technocrats attention looking into the ability to meet the demands of industrial and engineering structural requirements with its superior mechanical advantage such as high strength to weight ratio, effectively lower production cost as well as it accedes to traditional manufacturing methods. It was found that, the constituent reinforcing particles in the AMM are associated with certain control parameters which lead to drastic variation in composite’s material properties. Many researchers designed and developed hybrid AMM composites by examining it with the variations of reinforcement particles. Current research aims to summarize the literature available based on fabrication routes of the hybrid AMM composites.

1. INTRODUCTION

A new trend to incorporate materials that are lighter, stronger and comparatively economical exists in recent engineering applications. The need for these materials is also growing with the rapid development of new technologies met through using the extensive research on Metal Matrix Composites (MMC) with various reinforcement particulates. Composites consists of two phases one is continuous phase (Matrix) and the other is discontinuous phase (Reinforcements). The introduction of particulate reinforcement is to render the product economical by incorporating superior mechanical, thermal, and tribological properties. Consequently, the appropriate selection of reinforcements, matrix and processing techniques allows the production of custom materials to meet specific requirements of engineering. The hybrid composites of aluminum metal matrix (AMM) are gaining technocrats attention looking into the ability to meet the demands of industrial and engineering structural requirements with its superior mechanical advantage such as high strength to weight ratio, high stiffness to weight ratio, wear resistant behavior, effectively lower production, cost as well as it accedes to traditional manufacturing methods [1-4].

Extensive research has been carried out on the corrosion, mechanical, wear behavior of hybrid AMC, use diverse aluminum alloy (Al-alloy) and particulate reinforcement consisting of ceramics, oxides and carbides, for example silicon carbide (SiC), aluminum oxide (Al2O3) and boron carbide (B4C). However, these particulate reinforcement uses in the Al-alloy has led to increased composite toughness, which is undesirable when the material is machined after a composite has been produced. The use of many reinforcements in the aluminum alloy eliminates issues caused by the application of single reinforcement sections in the AMM Composites. The hybridization of AMM composites (by
inclusion of multiple reinforcement) not only guarantees a better control of improved properties, but also remedies adverse effects. The development of hybrid AMM composites utilizes ceramic particulates as primary reinforcement, whereas composite strength is significantly better than any other reinforcement particle [5].

Several researchers extensively researched on inclusion of industrial and agricultural waste, for example rice-husk ash, graphite, fly ash, so on in hybrid AMM composites as secondary reinforcements. These hybrid composites are economic in nature because of their edge of accessibility as well as light weight because of lower in density. Apart from this, they also possess the enhanced wear and mechanical characteristics [6, 7].

This study examines briefly the process of producing hybrid AMM composites, the impact of various reinforcement particles and their structure, as well as, modern reinforcement technologies recently used on the mechanical and tribological properties were summarized and outlined.

2. MANUFACTURING OF HYBRID AMM COMPOSITES

The production of custom materials to meet specific requirements of engineering requires selection of suitable processing techniques. In the last 20 years many researchers extensively researched and refined the processing techniques to develop hybrid AMM Composites. Liquid state, Solid state processes are the three main categories of key technologies used in commercial or advanced production of hybrid AMM composites. The Casting methods and Liquid infiltration methods are two techniques through which the hybrid AMM composite is developed by incorporating particulate reinforcement into liquified Al-alloy. Stir castings, centrifugal die castings, vacuum die castings, squeeze castings are the various conventional casting route involve reinforcement above the Al-alloy’s solidus temperature and obtaining the desired cast by gravity pouring using a suitable die (Figure 1).

![Fabrication Routes for AMM composites](image-url)
2.1. Stir Casting Route

One of the most conventional economical production methods, stir mixing with gravity casting, is used to produce large and near-net-shaped Components from hybrid AMM composites. Mostly, such a method uses the stirrers, that are designed to increase the formation of vortex in the melt in order to ensure that reinforcement particles are uniformly dispersed within the matrix. The mold and molten metal temperature, speed and time of stirring, particulate feed rate, size of impeller and crucible are the production variables that influence composite’s properties and homogenous particulate dispersion. Also, the issue of the wettability of the reinforcing ceramic particulate required to be handled suitably (Considering particles relative density to that of the liquid metal) in order to facilitate the homogenous particulate dispersion. Figure 2a illustrates components and basic principle of stir casting, whereas literatures on AMM composites’ manufacturing through stir casting route summarized in Table 1.

| Reinforcement | Base material | Process Parameters | Findings | Ref |
|---------------|---------------|--------------------|----------|-----|
| SiC           | Al 6063       | S – 500 rpm; T – 10 m | Enhanced wear resistance. | [8] |
| TiB$_2$       | Al (99.8 %)   | S – 60, 180 and 300 rpm; T – 60 m. | SR-CT characterization confirms homogenous particle dispersion. | [9] |
| SiC           | A356          | S – 600 rpm; T – 7 m. | Composite’s tensile and compressive strength improved with 1.5 wt.% nano SiC. | [10] |
| SiC           | LM6           | S – 600 rpm; T – 10 m; BA – 45° | 31% and 34% improvement recorded for hardness and elongation respectively. | [11] |
| Fly ash       | Al            | S – 100 rpm | Reduced wear rate. | [12] |
| Bamboo Leaf Ash | Al – 4.5 % Cu | S – 600 rpm; T – 10 m | Hardness values improved. | [13] |
| SiC           | Al 6061       | S – 300 rpm; T – 30 m | Tensile strength and hardness improved. A shift in ductile to brittle fracture behavior identified. | [14] |
| Al$_2$O$_3$   | Al 6061       | S – 200 rpm; T – 10 m; | Hardness, yield point, tensile strength improved. | [15] |
| TiC           | Al 6061       | S – 300 rpm; T – 15 m; BA-30° | Up to 300 rpm stirrer speed tensile strength increased. | [16] |
| SiC           | Al            | S – 500 rpm; T – 15 m. | Hardness improved. | [17] |
| TiB$_2$       | Al 6061       | S – 350 rpm; T -15 m. | Tensile strength improved. | [18] |

Legend: S: Speed; T: Time; BA: Blade Angle.
2.2. Squeeze Casting Route

Defect-free and near net shape structures can be manufactured through route of squeeze casting whereas it possesses advantages of as forging well as casting. Reduced porosity and higher surface finish qualities possessed by components produced through this route. In this route die cavity, filled with liquefied metal, cured under high pressure. Figure 2b shows schematic illustration of the squeeze casting basic principle, whereas literatures on AMM composites’ manufacturing through squeeze casting route summarized in Table 2.

| Reinforcement                | Base material | Squeeze Pressure | Findings                                                        | Ref.   |
|------------------------------|---------------|------------------|-----------------------------------------------------------------|--------|
| Diamond particles            | Al 1060       | 15 MPa           | Bending strength and thermal conductivity improved 124 % and 89 % respectively. | [19]   |
| PAN                          | Al            | 30, 50 & 70 MPa  | Tensile strength Improved                                        | [20]   |
| SiCw                         | Al 6061       | 1800 kN          | Enhanced Mechanical Characteristics                              | [21]   |
| MWCNT                        | Al            | 100 MPa          | Interfacial pore reduced.                                        | [22]   |
| Aluminosilicate fiber        | Al 6061       | 40 MPa           | Shrinkage, preform breakage and porosities reduced               | [23]   |
| WO₃, aluminium borate whiskers | Al          | 80 MPa           | Tensile and yield strength of the composite improved             | [24]   |
| Short carbon fibers          | A413          | 80 MPa           | 60 % and 100 % improvement recorded in composites’ tensile strength and hardness value respectively | [25]   |
| Al₂O₃                        | AlSi12        | 100 MPa          | Composites’ thermal conductivity, flexural strength, fracture toughness and hardness improved. | [26]   |
| Al 6101                      | A356          | 30 MPa           | Interfacial inclusion and pore reduced                            | [27]   |

Legend: MWCNT: Multi Walled Carbon Nano Tube
2.3. Gas Pressure Infiltration (GPI) Route

In the infiltration route, the reinforcing particulates shaped into a die-like preform, as well as, the capillary forces cause the molten AMM to wet and fill the entire porosity in this form. Furthermore, additional exterior mechanical force can be required in order to overcome the resistance forces induced by drag and capillary action [15]. The pressure required when mixing the matrix and the reinforcing materials is considered to depend on the frictional forces involved in the process, because of the viscosity of liquefied matrix filling the ceramic preform. Composition of preform made of ceramic material alloy, surface morphology, time and temperature are the different factors that influence ceramic preform’s wettability by the liquefied Al-alloy [24, 34]. Figure 3a shows schematic illustration of the Gas Pressure Infiltration principle, whereas literatures on AMM composites’ manufacturing through Gas Pressure Infiltration route summarized in Table 3.

![Schematic illustration of Gas Pressure Infiltration and stages of Powder Metallurgy (PM)](image)

**Figure 3**. Schematic illustration of (a) principle of Gas Pressure Infiltration (b) Stages of Powder Metallurgy (PM)

**Table 3.** AMM Composites fabricated by Gas Pressure Infiltration route.

| Reinforcement | Base matrix | Process parameters | Findings | Ref  |
|---------------|-------------|--------------------|----------|-----|
| Ti-coated diamond | Al and Al-Si | T – 1000°C; HT – 30 m; P – 10 MPa | Very low coefficient of thermal expansion, as well as, highest relative density and Thermal conductivity recorded for Si (12.2 %) / Al composite | [28] |
| Ti-coated diamond | Al-7Si | T – 700°C; HT – 10 m; P – 1.2 MPa | The reinforcement and the matrix possess Strong interfacial bonding between them | [29] |
| Ti-coated diamond | Al | T – 800°C; HT – 20 m; P – 1.00 MPa | Higher thermal conductivity recorded for lower Ti coating thickness. | [30] |
| diamond and (0.5 - 4.0 wt.%) Ti | Al | T – 800°C; HT – 20 m; P – 1 MPa; ATM – Ar | Higher content of Ti improved compressive, tensile bending and Young’s modulus values | [31] |
| Ti-coated diamond | Al | T – 800°C; P – 5 MPa | 117% improvement in the thermal conductivity recorded due to Ti coating on diamond reinforcement | [32] |
| SAFFIL | Al-Ag-Mg-Cu | T – 750 and 780 °C; P – 1, 2 and 3 MPa | 3 MPa and 750 °C was recorded as optimum pressure and temperature. | [33] |
| Material                                      | Base Material | Conditions                        | Recorded Properties                                                                 | Reference |
|-----------------------------------------------|---------------|-----------------------------------|-------------------------------------------------------------------------------------|------------|
| Ti-coated diamond                             | Al            | T = 800°C; HT = 20 m; P = 1.00 MPa; ATM = Argon | Improvement in compressive, tensile, bending and yield stress recorded with higher coating time (Ti-Coated Diamond) | [34]       |
| Diamond                                       | Al            | T = 700, 800, 850 °C; P = 0.1, 0.2, 0.5, 0.8, 1.0, 2.0 and 3.0 MPa | Improvement in interfacial bonding recorded with infiltration pressure and temperature. | [35]       |
| Diamond                                       | Al            | T = 760 and 850 °C; HT = 45 min. | Improvement in thermal conductivity (680 W/mK) recorded at lower temperature higher contact time. | [36]       |
| TiC coated diamond particle                   | A356          | T = 750 °C; HT = 0 min.            | Recorded composites’ thermal conductivity and coefficient of thermal expansion       | [37]       |
| SiC/diamond                                   | A356          | T = 750 °C; HT = 0 min.            | Influenced coefficient of thermal expansion and thermal conductivity depends upon diamond particles wt%. | [38]       |
| Ti – coated diamond                           | A356          | T = 750 °C; P = 1.5 MPa HT = 20 m | AMM composites’ thermal conductivity depends on Ti coating                           | [39]       |
| Diamond                                       | Al and AlSi7  | T = 750 °C; HT = 5 m; P = 100 MPa | Recorded thermal conductivity Variation                                               | [40]       |
| Ni – coated carbon fibers                     | A357          | T = 720 and 750 °C; P = 300 kPa   | With higher melting temperature, improvement up to 99 % in relative density recorded | [41]       |
| Diamond                                       | Al            | T = 750 °C; HT = 5 m; P = 100 MPa | Thermal conductivity value recorded with 130 W/Mk (Min) and 670 W/Mk (Max).           | [42]       |
| Metallic glass (Ni60Nb20Ta20)                | AlSi12        | T = 660 °C; HT = 2 hours; ATM = Ar | At right angle to direction of infiltration improvement in young’s modulus and yield strength recorded | [43]       |
| Graphite                                      | Al            | T = 750 °C; P = 8 MPa; ATM = Inert | A 110% improvement recorded in flexural strength, whereas drastic reduction in composites’ coefficient of thermal expansion recorded with almost one third of monolithic aluminum. | [44]       |
| SiC/FeNi50                                    | A356          | T = 670, 690, 710 and 730 °C; HT = 2, 4, 6, 10, 14, 18 m | With higher infiltration temperature reduced Bending strength recorded               | [45]       |
| GraphaneNano Platelet coated B4C              | Al-Si         | T = 800 ± 5 °C P = 800 kPa        | Enhanced wear resistance                                                            | [46]       |
| Ni coated carbon fibers                       | 2014 Al       | T = 730 °C; HT = 2 m; P = 50 kPa  | Composites’ elongation reduced, whereas tensile strength and modulus                 | [47]       |
| Metallic glass (Ni60Nb20Ta20)                | AlSi10Mg      | T = 660 °C; HT = 2 h; ATM = Ar    | Enhancement in yield strength and young’s modulus recorded                           | [48]       |
| Al2O3/SiC                                     | Al            | T = 650, 700, 750 and 800 °C; P = 1, 2 and 3 MPa | Higher bending strength and density recorded with improvement in infiltration temperature | [49]       |

Legend: T: Temperature; P: Pressure; HT: Holding Time; ATM: Atmosphere; N: Nitrogen; Ar: Argon.
2.4. Powder Metallurgy (PM) Route
Powder metallurgy (PM) is one of the extensively practiced technique in solid state route following sintering process. It can manufacture net shape components by removing the further processing requirements to get the final product. Comparative lower-operational temperatures improve kinetic control at the interface, making PM technology attractive. A unique blend of matrix alloys and microstructural refinements can be employed so that the reinforcing particulate used can be easily reinforced. Composites’ Processing in PM technique involve sintering (by heating) of Green Compact (compacted blended powders), by uniaxial pressing, typically at the desirable temperature of the manufacturing atmosphere (inert/vacuum) in order to achieve the sintered structure. In addition to this, microwave sintering and spark plasma so on are different methods used for sintering the reinforcement particulates according to the source of energy. In past few decades, extensive research and advancements has been carried on composites’ PM technique that uses AMM with reinforcing particulate Al, Al₂O₃ powder, so on significantly. The uniform blend of certain composition of Al powder, particulates reinforcement and additives are compacted into preform. Not only issues of phase transformations, heat affected zones and residual thermal stresses, but also, issues like limited sample dimensions and laser/electron beam reflectivity encountered during this process. Apart from this, higher cost, particulates agglomeration and consumption of energy are the significant issues behind the lack of extensive industrial implementation of PM technique. Figure 3a shows schematic illustration of the stages in the PM processing, whereas literatures on AMM composites’ manufacturing through PM route summarized in Table 4.

| Reinforcement   | Base matrix | Process parameters | Findings                                         | Ref. |
|-----------------|-------------|--------------------|--------------------------------------------------|------|
| Graphene        | Al (98 %)   | MS – 300 rpm ST – 560 °C TS – 4 h | Improved hardness and tensile strength            | [50] |
| Graphene        | Al (99 %)   | ST – 550, 600 and 630 °C TS – 60, 120, 180, 300 m | Hardness and density reduced with higher TS       | [51] |
| Graphene        | Al (99.9 %)| MT – 1, 3- and 5 h ST – 500 °C TS – 0.5, 1, 2, 3, 4, 5 h ATM – Argon | Composites with high hardness were developed.     | [52] |
| SiO₂            | Al (99.5 %)| MT – 2 h ST - 610°C | Increment of 24.8 % and 41.8 % recorded in composite’s hardness and tensile Strength respectively | [53] |
| Graphene oxide  | AlMg₅       | MT – 20 h P – 570 MPa ATM – argon | Properties improved with homogenous particle distribution. | [54] |
| SiC and B₄C     | Al          | P – 150 MPa ST – 610° | Hardness improved                                | [55] |
| TiO₂(nm size)   | Al          | P – 104 N/cm² ST - 450 C ATM - argon | Enhanced hardness and resistance to wear         | [56] |

Legend: MS: Milling speed; MT: Milling time; ST: Sintering temperature; P: Pressure; ATM: Atmosphere; TS: Time of Sintering
2.5. Equal Channel Angular Pressing (ECAP)

For ultra-fine grain materials, ECAP has proved to be a reliable production process. This technique can be used as a primary manufacturing route to develop the new composite as well as to refine the grain structure of the composites (developed through other route) as a secondary manufacturing process that will lead to enhanced mechanical properties. There are two channels of same shape and size i.e. of equal cross sections, intersecting usually at 90° through which billet is passed to undergo severe plastic deformation. Figure 4a shows schematic illustration of the ECAP principle, whereas literatures on AMM composites’ manufacturing through stir casting route summarized in Table 5.

| Reinforcement | Matrix | Dies | Findings                                                                                           | Ref  |
|---------------|--------|------|---------------------------------------------------------------------------------------------------|------|
| Fly ash (Coarse / Fine) | Al     | Back pressure-equal channel angular consolidation technique | Effective homogenous particle distribution in the base matrix | [57] |
| Titanium aluminide | Al     | CCS - circular (dia - 20 mm rotation angle - 120°) | Improvement in strength recorded whereas ductility reduced | [58] |
| SiC           | Al     | CA - 120 C ECAP (route Bc) | Porosity Reduced | [59] |
| SiC           | Al     | CCS (10 mm x 10 mm) CA - 90 | Uniformity of dispersion of SiC improved with shear strain. | [60] |
| SiC           | Al     | CCS (19.5 mm x 19.5 mm x 50 mm) CA - 90          | The pressing has positive influence on size, shape and dispersion of particulate reinforcement | [61] |
| 8wt.% Bi      | Al     | CA - 90 | Refined grains and porosity reduced. Recorded improvement in tensile, hardness and compressive strength. | [62] |
| SiCw          | LD7    | CA - 90 | After pressing, achieved preferred orientation and uniform dispersion of the particulate reinforcement | [63] |

Legend: CCS: Channel Cross Section; CA: Channel Angle

![Figure 4. Schematic illustration of principle of (a) Equal Channel Angular Pressing (b) Friction Stir Processing](image-url)
2.6. Friction Stir Processing (FSP)

The joining of metals takes place through severe plastic deformation that occur in FSP. This is one of the solid-state joining processes derived from friction stir welding. It alters the base matrix properties as well as its enhanced surface properties make it advantageous. Enormous heat is generated when non-consumable tool, rotating at very high speed, comes in contact of Al. Transition of the desired section of contact metal occur to plastic zone due to the generated heat where the reinforcement particulate blends. Metal is allowed to flow and consolidate due to the transverse movement of the rotational tool along the base matrix. Figure 4b shows schematic illustration of the FSP principle, whereas literatures on AMM composites’ manufacturing through FSP route summarized in Table 6.

Table 6. AMM Composites fabricated by FSP route

| Reinforcement | Matrix | Process Parameters | Findings | Ref |
|---------------|--------|--------------------|----------|-----|
| RHA | Al 6061 | **TTS** - 60 mm/min; **TAS** - 1600 rpm; **Force** -10 kN | Tensile strength improved | [64] |
| E & S-glass fibers | Al 1100 | **TTS** - 25 mm/min; **TAS** - 1000 rpm; **TTA** - 3° | Mechanical behavior improved. | [65] |
| WC | Al | **TTS** - 60 mm/min; **TAS** - 1600 rpm; **Axial force** -10 kN, **TTA** -2°; **PD** -0.2 mm | Improvement in strength and hardness recorded and grains refined | [66] |
| SiO₂ (nm size) | Al 5052 | **TTS** - 20 mm/min; **TAS** - 1200 rpm | Achieved Homogenous dispersion of particulate reinforcement | [67] |
| TiC | Al 6082 | **TTS** - 60 mm/min; **TAS** - 1200 rpm **Load** -10 kN | Recorded wear rate | [68] |
| Micro and nano B₄C | Al 5083 | **TTS** - 25 mm/min; **TAS** - 1000 rpm. | Improvement in tensile strength and hardness recorded due to uniform blending of nano B₄C | [69] |
| TiC | Al 7075 | **TAS** -1000 rpm **TTS** 300 mm/min; **PD** -2.8mm | Reduced value of Micro hardness. | [70] |
| SiC | Al 5052 | **TTS** - 30 mm/min; **TAS** - 1075 rpm; **TTA** -2.5° | Improvement of 140, 75 and 60 % recorded in Hardness, Yield and tensile strength increased by respectively | [71] |
| MWCNT and B₄C | Al 5083 | Single pass FSP | Improvement of 40 & 20% recorded in Tensile strength and Hardness respectively | [72] |
| CNT, Graphite and Graphene | Al 6061 | **TTS** - 0.2 mm/min; **TAS** - 1100 rpm; **PD** -1.2 mm | FSP passes influence wear behavior | [73] |
| SiC | Al 7075 | FSP (Single / double pass) | FSP (double pass) improved dispersion homogeneity and grain structure | [74] |
| B₄C | Al 7075 | Various **TAS** | Intense grain refinement | [75] |
| Graphene nano-platelets | Al 5052 | **TTS** - 25 mm/min; **TAS** - 1250 rpm; **TTA** -3° | Mechanical behavior improved | [76] |

Legend: **TAS**: Tool Angular Speed; **TTS**: Tool Traverse speed; **TTA**: Tool Tilt Angle; **PD**: Plunge depth; **RHA**: Rice husk ash; **MWCNT**: Multi Walled Carbon Nano Tube
2.7. Process Control Parameters of the Selected Manufacturing Route

Several researchers highlighted that the composites’ mechanical, wear and thermal behavior critically depend on the process variable of selected manufacturing route [77, 78]. In order to develop the tailored properties in AMM composite these process parameters need to be controlled as per the available research. Figure 5 shows the schematic illustration of the process control parameters.

Figure 5. Schematic illustration of process control variables of the selected fabrication techniques

3. CONCLUSIONS

This research summarizes the development of various hybrid AMM composites through different methods. the advantages of hybrid AMM composites over monolithic materials has been elucidated in the current research. During composite fabrication, processability and properties of Al enable its extensive use as matrix material. Stir casting is the most economical and simplest process. However, it needs to be careful while handling the issues of reinforcement’s wettability and porosity. The development of surface properties such as hardness and resistance to wear for hybrid AMM composites was successful through friction stir casting whereas it was stimulating to optimize control parameters for development of desired properties. Pressure, temperature and die materials are the different process control parameter in Squeeze casting yet to explored. Advantages of both forging and casting as well as high casting yield makes the Squeeze casting an excellent process available in liquid routes. ECAP technique can be used as a primary manufacturing route to develop the new composite as well as to refine the grain structure of the composites (developed through other route) as a secondary manufacturing process. PM’s process control parameters need to be maintained appropriately at each processing stage. However, its applications restricted due to its expensive and
complicated die design, higher cost, particulates agglomeration and consumption of energy so on restricts PM application. AMM composite with excellent mechanical and wear properties can be developed by appropriate combination of reinforcement, Al-alloy and manufacturing route. During the solidification of composites, complete and comprehensive phase formation needs to be investigated in the future, depending on extensive study of non-equilibrium states' solidification features such as competitive growth and suppressed solidification reactions.

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