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REVIEW ARTICLE

Processing of nanoreinforced aluminium hybrid metal matrix composites and the effect of post-heat treatment: a review

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Abstract

The demand for cutting-edge materials with a high strength-to-weight ratio and economic considerations is steadily increasing. Lightweight materials such as aluminium (Al) and its alloys are attractive, but some properties such as low thermal stability and high wear rate limit the application of aluminium alloys (AA) to some extent. Many researchers have developed various composites to get around these restrictions and increase the performance of aluminium and its alloy. Metal matrix composites (MMCs) with nanoparticles have revealed greater mechanical and tribological properties compared with micron-sized reinforcements. Most engineering applications require materials with excellent multidimensional properties, which are difficult to achieve using single reinforced MMCs. Hybrid metal matrix composites (HMMCs) with superior properties are the latest trends in composite technology. The choice of reinforcement selection has a vibrant role in the manufacturing of hybrid metal matrix composites. Researchers face a major challenge in finding optimum reinforcement combinations and their corresponding concentrations. The manufacturing of nanocomposites is difficult due to their high surface area and energy. To determine the most effective reinforcement combinations for hybrid composites, this article addresses several nanoreinforcements, their effects, and the appropriate processing methods for aluminium and its alloys. Researchers have paid less attention to the impact of precipitation hardening in aluminium and its alloys; thus, this paper also considers the effect of post-heat treatment of aluminium composites.

Keywords Nanoreinforcements · Hybrid composites · Manufacturing of nanocomposites · Powder metallurgy · Heat treatment · Precipitation hardening

Abbreviations

Al	Aluminium
AA	Aluminium alloys
MMCs	Metal matrix composites
HMMCs	Hybrid metal matrix composites
AlMMCs	Aluminium metal matrix composites
AlMMNCs	Aluminium metal matrix nanocomposites
Cu	Copper
Mn	Manganese
Si	Silicon
Mg	Magnesium
Li	Lithium
Ti	Titanium
Ni	Nickel
RM	Red mud
FA	Fly ash
BLA	Bamboo leaf ash
CHA	Coconut husk ash
CTE	Coefficient of thermal expansion
CNTs	Carbon nanotubes
hBN	Hexagonal boron nitride
C_f	Carbon fibre
CoF	Coefficient of friction
PSR	Particle size ratio
MWCNTs	Multi-walled carbon nanotubes

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HVOF	High-velocity oxy-fuel
MA	Mechanical alloying
HEBM	High-energy ball milling
PCA	Process control agents
PM	Powder metallurgy
BPR	Ball to powder ratio
SPS	Spark plasma sintering
FSP	Friction stir processing
XD	Exothermic dispersion
UTS	Ultimate tensile strength
Al_2O_3	Aluminium oxide
TiC	Titanium carbide
Si_3N_4	Silicon nitride
SiC	Silicon carbide
B_4C	Boron carbide
Gr	Graphene
TiB_2	Titanium diboride
WS_2	Tungsten disulphide
MoS_2	Molybdenum disulphide
ZrC	Zirconium carbide

Introduction

Materials are the backbone of development: advanced or new age materials having high-temperature stability along with superior mechanical properties are highly recommended for the field of the automotive, aeronautical, marine industry, bio-medical industries, etc., which is worthwhile on an economical and eco-friendly basis (Raj Praveen et al. 2022). For improved performance, the monolithic materials are modified by composite materials through proper alloying and variation of microstructures to enhance the properties such as high strength-to-weight ratio, high thermal stability, and high wear resistance. Composites are the combination of two or more identical constituents, meeting superior properties to that of the materials which constitute them and they incorporate a wide range of materials whose properties can be custom made to satisfy certain design requirements. Due to higher ductility and ease of fabrication, metal matrix composites have become more popular and widely used than ceramic matrix composites and have enhanced ecological stability and stiffness than polymer matrix composites. The main benefit of the MMCs is their personalized mechanical, thermal and physical properties (Kainer 2006).

Hybrid composites consist of two or more reinforcements and have an inevitable role in replacing the older materials on account of their extraordinary strength-to-weight ratio, high stiffness, enhanced hardness, good wear resistance, and high fatigue life (Singh and Belokar 2021). Modulus of elasticity, porosity, density, coefficient of thermal expansion, and electrical and thermal conductivities are some of the other factors that are affected while reinforcing two or more constituents in the base matrix. The selection of optimum combinations of reinforcements is the major task in the fabrication of hybrid composites (Mattli, et al. 2021). Hybrid composites have exclusive features that highlight numerous design needs in an economical way compared with conventional composites. The main features of the hybrid composites include balanced strength and stiffness, lower weight and cost, and better impact and fatigue resistance.

Aluminium alloys (AA) are striking substitutions for ferrous materials for countless industrial applications. Nowadays, Al alloys are used as a replacement for cast iron in the manufacturing of engine blocks due to their weight reduction of up to 45%. According to a study, the usage of Al alloys in the manufacturing of engine blocks started in the 1970s and the usage of the same increased to 9.77% in 2014 from 2% in 1975 and it is expected to increase in the future (Alten et al. 2019; Dai et al. 2016). The use of steel, cast iron and Al alloys in light duty vehicles is shown in Fig. 1. The demand for aluminium matrix composites is increasing owing to their low density, high toughness, high strength-to-weight ratio, corrosion resistance, higher stiffness, improved wear resistance, etc. (Vani and Chak 2018).

A lot of research work is ongoing in the field of development of AlMMCs to improve the properties. In addition, most of the research work shows that reinforcement of single particles has enhanced any one of the properties by negotiating some other properties. These property negotiations can be improved by adding two or more reinforcements to AlMMCs to get better mechanical, metallurgical, and thermal properties at the same time. Aluminium has a lower density (2.7 g/cm^3) than other metals such as Titanium and Nickel and satisfactory thermal conductivity (237 W/mK) and electrical conductivity (0.03 μΩm). The major disadvantages of Al include lower melting point (660℃), Young's

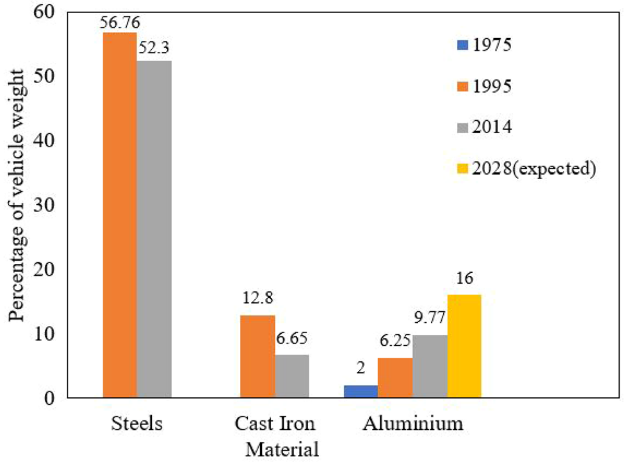


Fig. 1 Usage of steel, cast iron and aluminium in light duty vehicles (Dai et al. 2016)

modulus (72 GPa), ultimate strength (30 MPa), and hardness (40 HV). Magnesium-based matrix composites have comparable advantages with AlMMCs, but they are rarely used due to low thermal conductivity, low ductility, low fracture resistance, and their restrictions for production (Gupta et al. 2012). Light-metal composites such as AlMMCs validate better performance and extraordinary capabilities in severe environments. The application of AA in the automotive and aerospace industries involves thermal stability at raised temperatures. At temperatures above 150℃, Al alloys suffer a severe loss in strength followed by catastrophic softening with cumulative temperature, even though lots of attention is required to overcome the drawbacks such as poor tribological performance, low strength, hardness and corrosion resistance, which limits the application of Al and its alloy (Czerwinski 2020; Stojanovic and Igor 2018). For a better balance between the strength and ductility of AlMMCs, many efforts have been made to introduce hybrid reinforcements at different sizes into the composite (Xuan et al. 2021). To boost the properties of Al and its alloys, reinforcements in the form of ceramic particulates, whiskers, or fibres are added and thereby enhance mechanical and tribological properties.

Aluminium alloys are graded depending upon the major constituent element in the alloy. The aluminium alloy grades along with their properties and applications are tabulated in Table 1. Among the Al alloys, 7xxx grade Al alloys having zinc as the major alloying element are commonly used in structural applications. 50% of the Boeing 787 aircraft and 25% of Airbus A380 are using 7xxx alloys as structural materials (Manohar et al. 2021a; Mu et al. 2022). Weight percentage of various materials used in Boeing aircrafts are shown in Fig. 2. Some of the major alloys in the 7xxx graded alloys are AA 7050, AA 7055, AA 7068, AA 7075, AA7079, etc. AA 7075 is a high strength alloy commonly used in high-stress structural applications and the AA 7050 alloy has exceptional fatigue strength (Singh et al. 2021). AA 7075 have high toughness, high thermal and electrical conductivities, etc., but it is limited by its poor tribological and mechanical properties at elevated temperatures.

Reinforcements are commonly classified as organic and inorganic reinforcements. Inorganic reinforcements may be either ceramics–carbides, oxides, nitrides, borides, etc. or metallic phases. The various base matrix and reinforcement materials used for the production of MMCs are shown in Fig. 3.

The reinforcements are classified depending upon the shape such as particles, flakes or whiskers and fibres. Particulate reinforcements are smart due to their cost effectiveness, isotropic properties, light weight, and processing method similar to monolithic materials. Mechanical properties of particulate types of composites will be improved by dispersion strengthening and by restricting the dislocation movement (Warren 2004). Fibre-reinforced materials do not strengthen the continuous phase, but enhance the properties in relation of specific strength and stiffness in a room and at raised temperatures and make a strong composite. The fibrous reinforcement will be of short or long fibre type and this may be classified on the basis of direction and orientation of the fibres (Chawla and Shen 2001). Fibre-reinforced composites depend on mechanical properties of both the reinforcing fibre and matrices, orientation of the fibres, aspect ratio of the fibres, nature of the bond between the matrix and fibre. The quality of the composites depends on the propagation of the flaw. When compared with bulk

Table 1 Different alloy grades of aluminium

Alloy series	Major alloying element	Properties	Heat treatment	Applications	References
1xxx	–	Low strength, electrically conductive, highly reflective	Not heat treatable	Electrical conductors, decorative components	Mattli et al. (2021)
2xxx	Copper (Cu)	High strength, low corrosion resistance	Heat treatable	Forged and machined components, aircraft fittings	Thomas (2021)
3xxx	Manganese (Mn)	Medium strength, good formability	Not heat treatable	Storage tanks, beverage cans	Liu and Chen (2015)
4xxx	Silicon (Si)	High castability and machinability, low ductility	Not heat treatable	Castings	Sharma and Jung (2017)
5xxx	Magnesium (Mg)	Excellent corrosion resistance, medium strength	Not heat treatable	Aerospace and marine applications	Menachery et al. (2013)
6xxx	Magnesium and silicon (Mg and Si)	Medium–high strength, easily extruded	Heat treatable	Doors and windows, exterior fittings in automobile	Miller et al. (2000)
7xxx	Zinc	High strength, prone to stress applications	Heat treatable	High structural applications—aircraft, automobile fields, etc.	Singh et al. (2021)
8xxx	Li	High strength	Not heat treatable	Aerospace industry	Starke Jr et al. (1996)

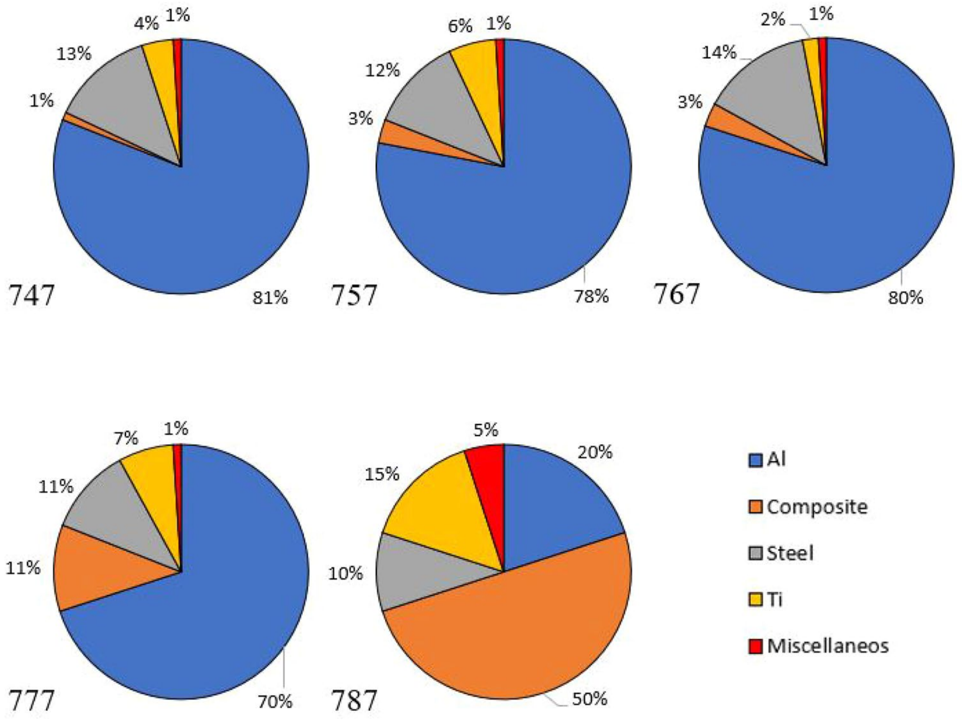


Fig. 2 Usage of various materials in Boeing aircrafts (Warren 2004)

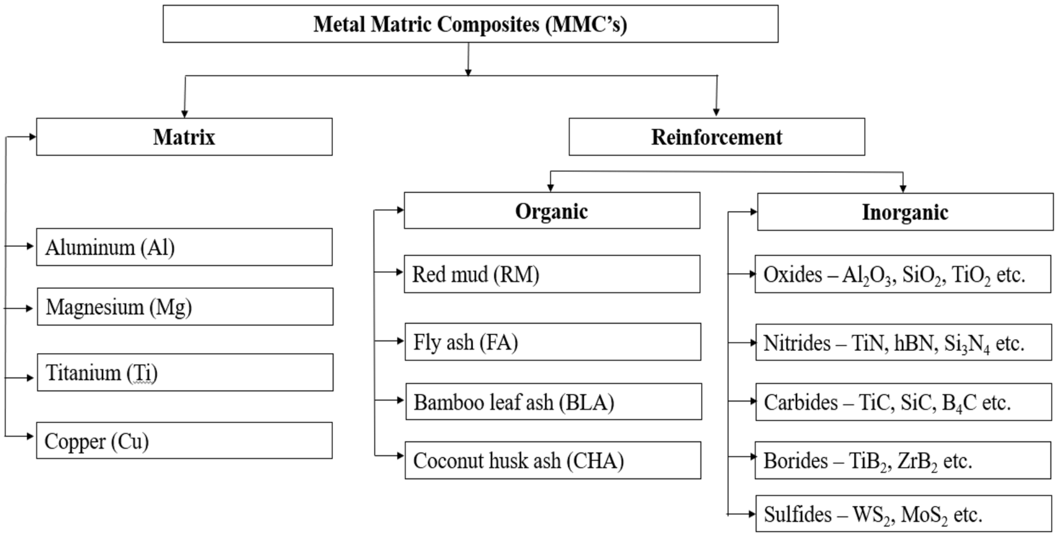


Fig. 3 Various base matrix and reinforcements used for the production of MMCs

materials, the fibre composites will restrict the propagation of the flaws and strengthen the composites (Haghshenas 2016). The strength of the fibre-reinforced composites is directly proportional to the fibre content and these composites are elastic in nature. These composites weaken gradually depending upon type of load, but they will not fail in a catastrophic way. When load is applied to the composites, there may be a chance of sliding the fibres. To get proper bonding, higher pressures during the time of fabrication as like in squeeze casting or coating the fibres is done (Vassel 1999). For the last few years, carbon fibres (C_f) strengthened AlMMCs have concerned ample care for their outstanding features such as high specific strength and specific modulus, better flexibility, low density, and low coefficient of thermal expansion (CTE) (Bahl 2021; Frank et al. 2012). Carbon fibres are rarely reinforced into MMCs, due to the complications that come through the manufacturing of the composites. The poor interfacial bonding triggered by interfacial reactions and poor wettability of C_f and Al matrix can be eradicated by depositing nickel coating on C_f surface (Xuan et al. 2021). The deposition of Ni coating on the C_f surface results in good interfacial bonding between the carbon fibre and Al matrix and interfacial reactions can be eliminated (Chandel et al. 2021; Chand 2000). Manufacturing difficulties and low costs favour the particulate reinforced composites over whisker or fibre-reinforced composites. The melting point, density, tensile strength, thermal conductivity, and properties of some of the inorganic reinforcements are itemized in Table 2.

The strength and ductility of the composites are influenced by the reinforcing particle size. Mechanical properties of the composites will be enhanced when the particle size reduces from micro- to nanoscale (Chandel et al. 2021; Tjong 2013). The micron-sized particles are probably to be cracked during the plastic deformation owing to stress concentration at the matrix/particle interfaces and thereby lowering the tensile properties of the composites (Chandel et al. 2021; Mu et al. 2021) Low percentage of nanoreinforcement addition will improve the properties such as ductility, fatigue, and strength, when compared with micron-sized reinforcement. The reinforcement of nanoparticles in the MMCs have shown superior properties to microsized particle-reinforced MMCs. Because of the substantial reduction in penetration defect and the formation of intermetallic compounds, hybrid nanocomposites are preferable to mono-reinforced composites (Sharma et al. 2015). Some of the nanoreinforcements include carbon nanotubes (CNTs), nanographite, alumina, silicon carbide, and hexagonal boron nitride (hBN). The nanosized particles have high surface energy and surface area, when compared with micron-sized particles which make it difficult to achieve uniform distribution in the matrix (Cabeza et al. 2017). Aluminium matrix nanocomposites (AlMMNCs) have been verified to be outstanding materials for the production of structural parts with enhanced properties for the aerospace and automobile industries (Mavhungu et al. 2017). TiB_2 particles both in micro- (5 µm) and nano- (20 nm) size were reinforced into A356. Composites formed by nanoparticles have shown improvement of 43% in tensile strength and 27% in toughness than the micro-reinforced composites. Improvements in mechanical properties were obtained by reinforcing 1.5 Vol. % of TiB_2 nanoparticles, but further addition of nanoparticles decreases the strength (Akbari et al. 2015).

The mechanical and thermal properties of the AlMMCs are strongly influenced by the microstructure, reinforcement type and abrasive nature, interfacial bonding, volume fraction and particle size of the reinforcements. Micron- and nanosized particles are added into the AlMMCs to enhance the properties such as improvements in strength-to-weight ratio, hardness, ultimate tensile strength, resistance to wear, and CoF. The particle size is one of the main factors in determining the properties of a composite (Faisal and Kumar 2018). The inclusion of harder ceramic particles into the softer Al matrix improves the hardness and decreases the ductility of base material (Kumar et al. 2018). Nanofillers are favoured over macrofillers because they increase not only the mechanical properties but also the functional properties such as self-lubrication. The tribological and mechanical properties of CNT and graphene nanoplatelets reinforced aluminium composites were discussed and demonstrated the self-lubricating behaviour of the composites during different tribological conditions (Moghadam et al. 2015; Tabandeh-Khorshid et al. 2016). The amount of reinforcement added into the matrix has a significant influence on the property evaluation of the composite. A low fraction of nanoreinforcement enhances the strength of the composite and higher amount will decrease the ductility, and the fibre reinforcement composites have better properties than micro/nanoparticle-reinforced composites due to their higher surface area. As per the studies, nanoreinforcements below 2 vol.% have shown superior properties and for the same attainment of properties, higher volume fractions of micron particles ($\gg$ 10%) are required (Reddy et al. 2017).

Particle size ratio (PSR) of the matrix and reinforcement plays a vital role in the uniform dispersion. For a fine microstructure, PSR should be closer to one and result in better mechanical properties and if the ratio is more than one, it leads to cluster or agglomeration formation (Slipenyuk et al. 2004). Lubricants are generally applied on contact surfaces to reduce wear losses and specifically in periodic applications lubrication is difficult, to overcome this difficulty, solid lubricants are added into the base material (Mittal et al. 2020). The tribological properties of the Al composites can be enhanced by reinforcing with self-lubricating reinforcements such as CNT, Gr, WS_2, MoS_2, and hBN because they impart better wear-resisting property under different environmental conditions. The reinforcement of hard ceramic particles enhances the mechanical and tribological properties of AlMMCs, but it abrades the counter material and releases wear debris (Fei et al. 2015). The addition of soft lubricants decreases the abrading behaviour of ceramic particles reinforced MMCs. It is reported that the addition of hBN, having a lamellar crystal structure improves the lubrication of the material (Podgornik et al. 2015). The hexagonal boron nitride (hBN), when combined with Al_2O_3 resulted in higher wear and mechanical properties in the hybrid Al metal matrix composites. hBN reinforcement in MMC prevents the fast wear rate of materials when it is exposed to the dry sliding condition (Rana et al. 2022). The addition of hBN particles into AA 7075 fabricated by the squeeze cast technique forms a stable tribo-layer and decreases the CoF and wear rate (Loganathan et al. 2021). The ceramic

Table 2 Properties and applications of commonly used inorganic reinforcements

Reinforcement	Melting point (℃)	Density (g/cm^3)	Tensile strength (MPa)	Thermal conductivity (W/mK)	Properties	Applications	References
Al_2O_3	2072	3.85–3.95	665	38.5	Better strength-to-weight ratio, better specific stiffness and strength	Cylinder heads, engine parts, brake disc	Sajjadi et al. (2012)
TiC	3160	4.93	258	20	High melting point, high thermal and chemical resistivity, excellent hardness	High-temperature structural applications	Namini et al. (2021)
Si_3N_4	2769	3–3.25	76	43	Better tensile strength and fracture toughness at peak temperatures, higher hardness	Automotive parts-hybrid bearings made from ceramics, rocker arm pads, turbocharger	Riley (2000)
SiC	2730	2.98–3.21	1625	20.7	High hardness, strength and toughness, resistance to wear and fatigue	Brake drum, propeller shaft, piston and connecting rod	Pensl et al. (2005)
CNT	3130	1.3–2.2	63,000	6000	Enhances electrical and thermal conductivities, better tensile strength, low CTE, better strength-to-weight ratio, low density, ductility and hardness	Coating for thermal barriers, biomedical applications, air craft landing gears	Popov (2004); Hussain et al. (2020)
B_4C	2763	2.4–2.52	569	42	Better hardness, thermal conductivity and wear resistance, high MP, low density, low specific weight	Ballistic and automotive applications, tank armour, intake manifolds, suspension components	Domnich et al. (2011); Thevenot (1990)
Gr	3600	1.6–2.26	76	114	Better thermal conductivity, self-lubricant	Cylinders, piston, heat sinks, discs	Prasad and Asthana (2004)
hBN	3000	2.3–2.27	83	350	Better electrical resistance and thermal conductivity, low coefficient of thermal expansion, better machinability, comparatively low dielectric constant, non-toxic	Electronic applications—high-frequency Cu clad laminates	Kim et al. (2014)
TiB_2	3318	4.5–4.54	373.6	26	High strength and better wear resistance	Thermal management fields, armour protection, ceramic cutting tools	Munro (2000)

particulates such as silicon carbide (SiC), alumina (Al_2O_3), and boron carbide (B_4C) would significantly improve mechanical characteristics of the composites. But the addition of solid lubricants that has a great potential to serve as secondary reinforcements resulted in superior mechanical and tribological properties (Chandel et al. 2021; Viswanatha et al. 2013).

The choice of reinforcement selection has a vibrant role in the manufacturing of hybrid metal matrix composites but the main task met by the researchers is to get optimal combinations of various reinforcements. The various properties of reinforcements such as high thermal conductivity, high strength-to-weight ratio, low density, better interfacial bonding, resistance to chemicals, fire, wear and corrosion are some of the main interests of the researchers (Rajak et al. 2019). To overcome the health hazards, special care is needed when reinforcing ultrafine nanocomposites (Moona et al. 2018). To evaluate the influence of the secondary reinforcements in the hybrid composites, the nanoreinforcements are to be taken at low weight fractions, either the same or half of the primary reinforcements. The studies reported that more than 2 wt. % nanoreinforcements result in agglomeration formation and decreases the mechanical properties (Kannan and Ramanujam 2017). Lot of research works has been conducted to process the nanoparticle-reinforced metal matrix composites, but lesser number of works is reported which reinforces nanoparticles into the aluminium alloy to improve their tribological properties without compensating the mechanical properties. In this review article, different types of reinforcements (both micro- and nanoparticles) added in to AA along with their property variations are discussed in detail. Different manufacturing methods for nanocomposite fabrication, the need of hybrid AlMMCs, which have balanced mechanical and tribological properties and difficulties in manufacturing nanocomposites are also deliberated in this paper.

Manufacturing of MMCs

The production of nanocomposites is a very difficult process and faces several hurdles such as random distribution of reinforcement particles, poor wettability, porosity, clusters and agglomeration formation during the fabrication. The main problem related to the manufacturing of nanocomposites is the van der Waal's force which limits in getting uniform reinforcement dispersion (Esawi et al. 2011). The main challenges in the processing of the AlMMCs include non-homogenous distribution of the particles, weak interfacial bonding, wettability issue and stability of the material under different condition. The manufacturing process of MMCs has a noteworthy effect on achieving the desired properties of the composite along with the cost. The different types of manufacturing methods are listed in Fig. 4.

In addition to the conventional fabrication techniques of MMCs, other methods include the electro-deposition method, chemical and physical layer deposition method, plasma spraying method, sputtering method, and molecular level mixing. The various processing routes used in MMC production are listed in Fig. 5. Particle agglomeration, poor wettability and interphase formations, and compatibility of the matrix with reinforcement are some of the key factors that depend on the fabrication of MMCs, and MMCs are fabricated depending upon the market needs.

The casting methods include stir or gravity casting methods, ultrasonic-assisted casting, compo-casting methods, infiltration or squeeze casting method, and centrifugal casting method. In stir-casting method, the reinforcement is added in to the base matrix in the liquid state and mechanical stirrer is used to get the proper dispersion of the particles in the matrix. This method is economical, flexible and simple among all the composite manufacturing process. During the solidification, the cooling rate will be changed from the surface to the centre. Due to this non-homogeneity of the

Fig. 4 Classification of manufacturing methods

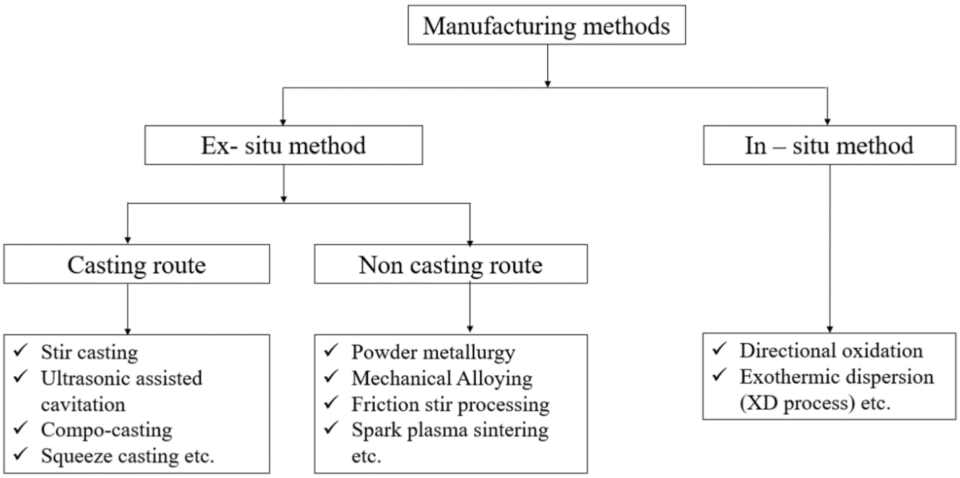


Fig. 5 Various processing routes used in MMC production (Thomas and Umasankar 2019)

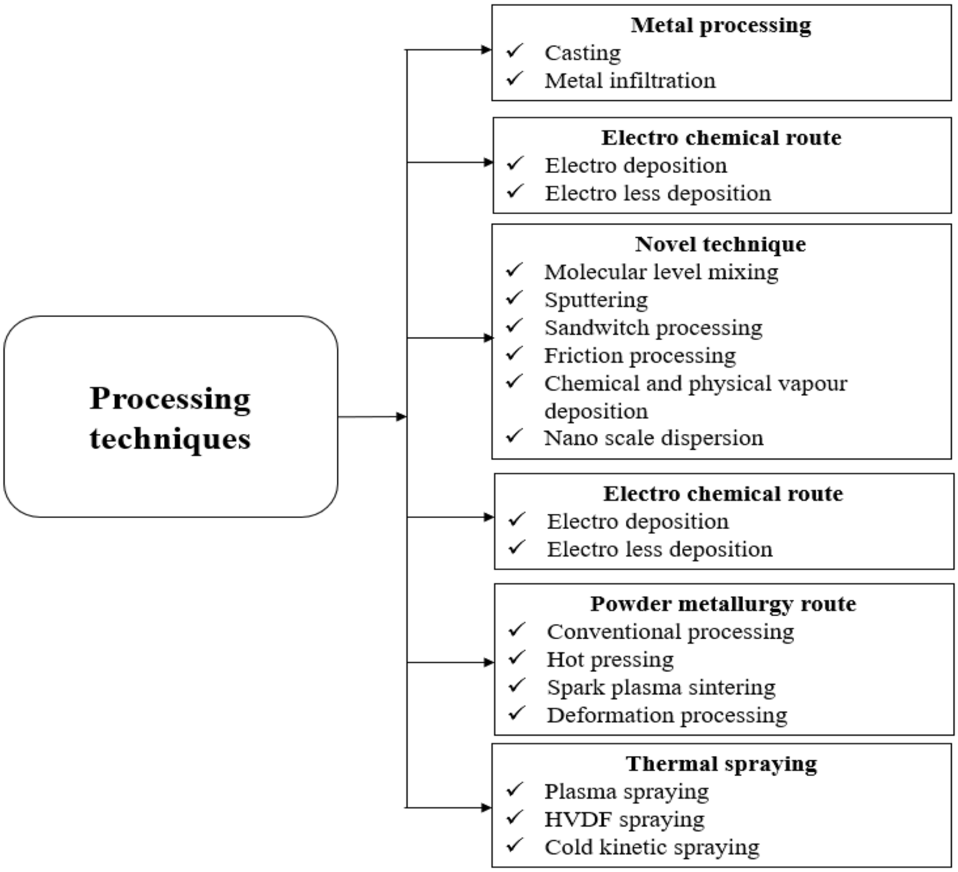
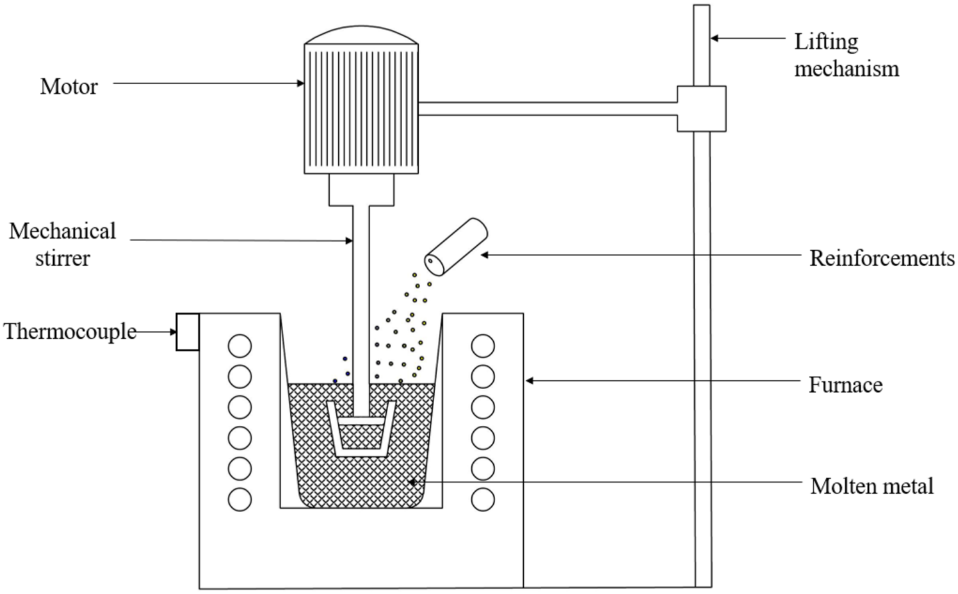


Fig. 6 Schematic diagram of stir-casting machine



constituents, poor wettability of the reinforcements happens in the matrix (Thomas and Umasankar 2019). The symbolic representation of stir-casting method is shown in Fig. 6.

Wettability of the reinforcing materials in the motel metal can be enhanced by preheating the materials before dispersing. Because of density differences between the continuous phase and the discontinuous phase, there may be a chance of sinking or floating of the reinforcement materials in the molten metal, which leads to non-homogenous dispersion. This non-homogenous dispersion leads to clustering of the particles and agglomeration tendency in the melt. Porosity, oxide presences and undesirable interfacial reactions are some of defects in the end results. To overcome the clustering of the particles along with agglomeration tendency and to improve wettability of the reinforcement particles, two stage stirring method is adapted. For the nanosized reinforcement particles having high surface energy and surface area, to avoid agglomeration tendency and low wettability, stir-casting method with longer stirring time is preferred but it results in oxidation of the molten metal and gas formation (Auradi et al. 2014). In comparing with stir-casting method which is having longer stirring time for homogenous dispersion of the particles, ultrasonic-assisted casting method which uses ultrasonic vibration principle to uniformly disperse the particles by creating ultrasonic cavitation effect is preferred (Idrisi and Mourad 2019). In compared with stir-casting method, ultrasonic-assisted stir-casting method is not economical and rarely preferred.

In Compo-casting or rheocasting process, the reinforcements are added to semi-solid metallic matrix with the help of mechanical mixers. This method can be applied to increase the wettability of the reinforcements and to reduce the agglomeration tendency. As this method is employed in semi-solid state, it saves large amount of energy and operates at lower temperatures in comparison with liquid metal matrices (stir casting), and restrict any types of reactions between the reinforcements and matrix and also tool life will be extended. It is reported that compo-casting method improves the wettability and uniform distribution of SiC particles in the Al 356 cast alloy than the stir-casting method (Amirkhanlou and Niroumand 2010). MWCNTs were added into the AA 2219 and the mechanical properties were studied. The results show that the whole possibilities of nanoreinforcement were not achieved in composites and suggest that nanoreinforcement through casting route is not sufficient to get uniform distribution of the particles in the metal matrix (Thomas et al. 2020).

Squeeze casting method is done at high pressures and the application of this pressure in the molten metal during the solidification stage may lead to change in cooling rate and melting temperatures, reduction of shrinkage porosities and gas formation. The effect of parameters such as hardness, macrostructure and density of LM13 alloy fabricated by squeeze casting is discussed and reported that squeeze casting method will enhance the macrostructure and hardness of the composites (Maleki et al. 2006). The increase in the applied pressure will result in better hardness and smaller grain size. The conventional casting results in pore defects, resulting drop in the mechanical properties and the consistency of the products. Therefore, stir-casting method followed by squeeze operation is done to reduce the pores in the microstructure of the material (Gurusamy and Balasivanandha Prabu 2013).

Solid-state processing method overcomes the limitations of liquid-state processing technique, where the material is processed under the melting temperature of the matrix material. In this method, it overcomes the oxidation problems of metal and reinforcements. To get proper bonding and interfacial interaction, high pressure is applied at raised temperatures, but below the melting point of the base material. Solid-state processing technique can properly disperse nanoparticles and boost the mechanical properties of composites. This method also reduces the energy costs and keeps the chemistry of material unbroken. This method includes diffusion bonding, cold spraying, mechanical alloying, powder metallurgy, and friction stir processing.

Diffusion bonding method is used to manufacture plates, tubes, shaft structural components, etc. Long fibres are reinforced into the chemically surface-treated matrices for better inter diffusion. Matrix and reinforcement are loaded in a prearranged order and hard-pressed at high temperatures to verify superior bonding. This method is widely accepted due to controlled volume fraction addition of reinforcements and fibre orientation (Kazakov 1985).

Cold spraying is another type of solid-state material deposition method, which is commonly used for fabricating composites and coatings. The particles having micron size which is in powdered state are bonded to a substrate by high-velocity impact and plastic deformation happens. Diverging–converging nozzle is used to accelerate the particles at high velocity through pressurized or hot gas. Regardless of heating the process, and to provide higher acceleration and to facilitate plastic deformation through thermal softening, feedstock remains in the solid state throughout the process. In comparison with thermal spray techniques, the powders are not melted in this method (Assadi et al. 2016). High-velocity oxy-fuel (HVOF) is used to coat Cr_2O_3 on Al 6061 alloy and the mechanical properties were studied. The different parameters were optimized to get the best mechanical properties (Pradeep Kumar et al. 2021).

Mechanical alloying (MA) is a solid-state manufacturing method concerning repeated cold welding, fracturing and rewelding of mixed powder particles in a high-energy ball mill to yield a homogenous material. High-energy ball milling (HEBM) uses high-energy impressions from high-frequency hard material balls such as tungsten carbides in attrition mill or mechanical milling of processed powders in the controlled atmosphere. Due to the high-energy impact between the particles, there may be chance of increase in the particle size due to cold welding, additional impacts bring strain hardening effects in cold-welded particles, and more collisions induce fracture of particles directed to decrease the particle sizes (Manohar et al. 2018). Process control agents (PCA) or surfactants are periodically added to reduce the effect. Morphological changes occurring in

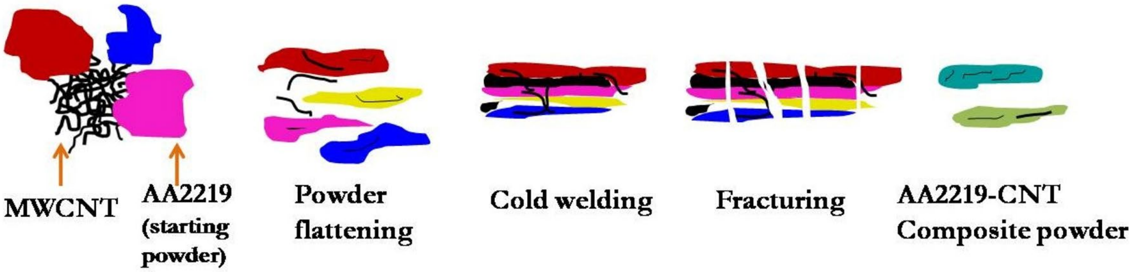


Fig. 7 Morphological changes occurred in AA 2219–MWCNT during HEBM (Thomas et al. 2019a)

AA2219–MWCNT during high-energy ball milling is represented in Fig. 7.

Powder metallurgy (PM) is one of the highly economical methods for bulk manufacturing of near net-shaped composites with high precision and dimensional accuracy, having good mechanical and structural properties. In powder metallurgy method, the fine powders are precisely mixed and blended, compacted to a shape using a die followed by sintering in the controlled conditions. HEBM is the most commonly used powder mixing technique in PM. Complex shaped products with less scrap loss can be produced by PM process. The compaction pressure, sintering temperature, soaking time, binding agent acts as a significant role in determine the final properties of the composite (Deepanraj et al. 2021). Figure 8 shows the schematic diagram of the powder metallurgy process. Uniform distribution of the nanoreinforcements in the metal matrix composites, along with enhancement in overall properties, can be achieved by powder metallurgy (Umasankar and Shijo 2018).

Particle agglomerations in the MMCs manufactured by PM process affects the material and functional properties of the composites and this can be eradicated by proper milling of the particles (Canakci and Varol 2015). In PM, uniform distribution of reinforcement particles in the base matrix is attained by ball milling process, and to get homogeneous distribution of reinforcement particles, longer milling time is desirable (Varol and Canakci 2013; Mendoza-Duarte et al. 2015). It is reported that ball milling for longer time will damage the structure of the CNT causing reduction in the expected properties, and suggested that sonication before the ball milling process will uniformly disperse CNT in the Al matrix and claimed that structure of the CNTs remain unchanged after ball milling. For achieving uniform dispersion of the particles, ball milling with premixing process such as sonication (ultrasonication or probe sonication) and stirring (magnetic and mechanical) were preferred. Premixing helps in attaining uniform distribution at shorter milling time along with low ball to powder ratio (BPR) (Thomas

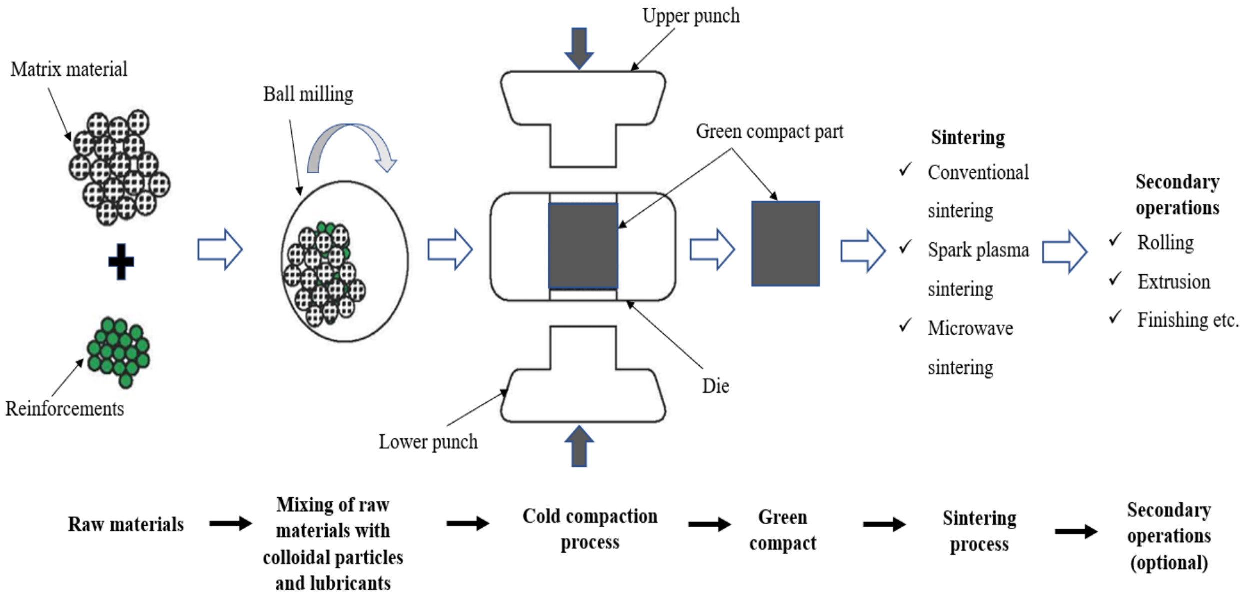


Fig. 8 Schematic representation of powder metallurgy method (Thomas and Umasankar 2019)

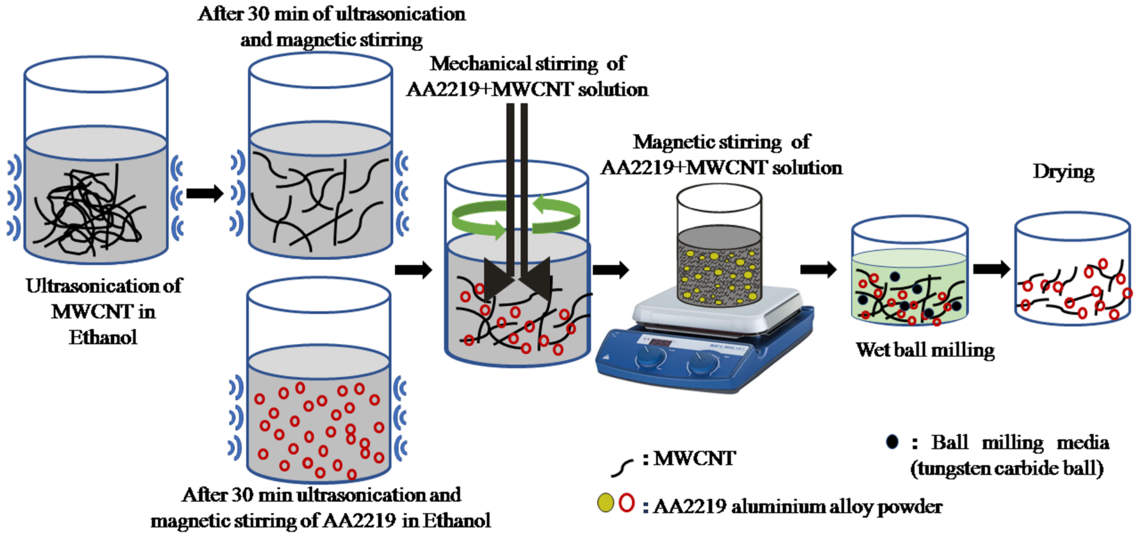


Fig. 9 The powder preparation steps of AA 2219 reinforced with MWCNT (Thomas, et al. 2019b)

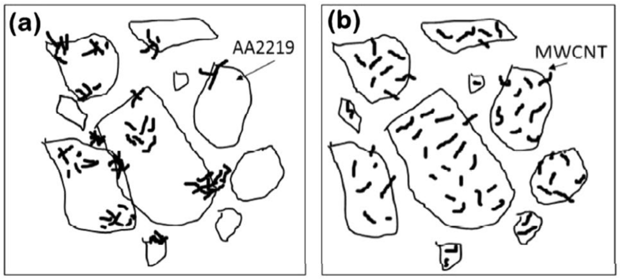


Fig. 10 Schematic representation of MWCNT in AA 2219 after **a** ball milling for 4 h, **b** premixing followed by ball milling for 4 h (Thomas et al. 2019b)

et al. 2019a). The powder preparation steps of AA 2219 reinforced with MWCNT along with premixing process is represented in Fig. 9.

In ultrasonication, ultrasonic waves at frequencies above 20 kHz are propagated into the liquid medium, whereas in probe sonication, a probe is immersed into liquid medium. In most of the cases, probe sonication is preferred than ultrasonication due to their effectiveness in processing nanomaterials and low agglomeration tendency (Thomas and Umasankar 2019). The dispersion of MWCNT in AA 2219 after ball milling for 4 h and premixing followed by ball milling for 4 h is represented in Fig. 10. After 4 h ball milling, MWCNTs were dispersed in the AA 2219 matrix but not uniformly dispersed, but after premixing followed by ball milling for 4 h, MWCNTs were homogeneously dispersed and distributed in AA 2219 matrix (Thomas et al. 2019b).

Powder metallurgy is a low-temperature manufacturing method which limits the atomic diffusion rate, interfacial reactions, unforeseen phase formation and have a close control of interface kinetics (Labib et al. 2018). The defects such as pores cannot be eliminated in the PM process which destroys the mechanical properties of the composite by restricting the diffusion of the particles at the time of sintering. Longer sintering time may lead to unwanted reactions between the matrix and reinforcement particles, resulting in the formation of intermetallic compounds (Viala et al. 1997). Some of the works reported that these intermetallic compounds act as precipitates and enhance the mechanical properties of the composite. To control the uniform dispersion of reinforcement particles in the base matrix and to avoid unwanted chemical reactions, PM is equipped with modern sintering methods such as spark plasma sintering (SPS) and microwave sintering (Li et al. 2017; Manohar et al. 2021a).

In spark plasma sintering (SPS), sintering is done at short intervals (5–10 min) at a temperature of 450 to 550℃, depending upon the base material. Short sintering time reduces the formation of unwanted intermetallic compounds (Mamedov 2002). On/off DC pulse is given to powder particles resulting high-temperature plasma and ensures strong interface bonds. AA 2219 is reinforced with MWCNT at 0.5, 0.75, 1, and 2 wt. % and consolidated by spark plasma sintering method. The mechanical studies claim that mechanical properties were improved upto 1 wt. % MWCNT and beyond that, agglomerations were reported (Thomas et al. 2020). The schematic representation of spark plasma sintering process is shown in Fig. 11. Micro-, nano- and bimodal particles of tungsten carbide (WC) are reinforced to Al base material through SPS method and improvement in mechanical properties for nanoparticles reinforced composites is reported. Due to the direct compaction and sintering, the pores can be

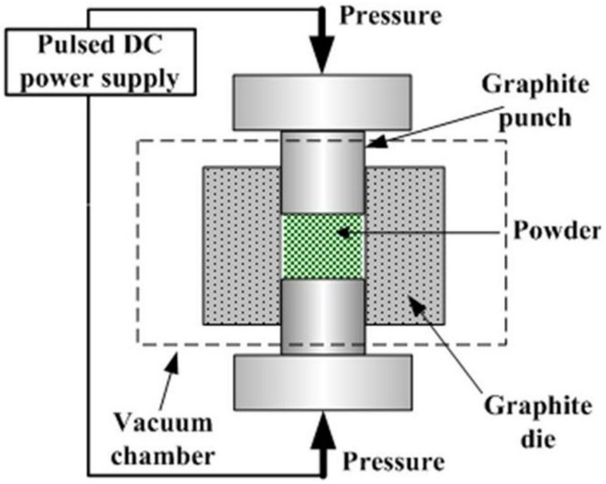


Fig. 11 Schematic representation of spark plasma sintering process (Thomas et al. 2020)

reduced through SPS process and the longer exposure of high temperatures avoids oxidations to a great extent. Changes in the SPS temperatures reduces the porosity level to some extent and variation in compaction pressure and sintering time did not show any notable differences (Pakdel et al. 2017).

Internal heat generation is the key principle in microwave sintering process which helps in achieving strong interfacial connection between the particles (Mattli et al. 2019) and these heat generation is due to the absorption of microwaves happening inside the ceramic particles (Ashwath and Anthony Xavior 2018). Studies shows that microwave sintering process expands the mechanical properties of the composite in comparison with the conventional sintering. In additional, vacuum hot pressing before microwave sintering resulted in strong interface bonds of the composites (Reddy et al. 2017).

Friction stir processing (FSP) operated lower than the melting point of the substrate resulted in less interfacial reactions between the particles. Frictional heat is created by non-consuming rotating tool by raising the local temperature and then plastically deformed. FSP process will improve the microstructural property. It is reported that by friction stir processing method, uniform dispersion of the particles in the matrix along with good bonding is achieved when Al 5083 is reinforced with SiC (Mishra et al. 2003).

The in situ processing techniques encompass chemical reactions between matrix and reinforcements; this method improves thermodynamically steady reinforcement in the matrix. Compared to other processing methods, in situ processing methods have good wettability, better uniform homogenous dispersion and are less economical. The molten metal matrix will be one of the reacting elements and other may be either gaseous phases or fine powder particles. Exothermic dispersion (XD process), reactive hot pressing, directional oxidation, etc. are some of the methods in in situ processing techniques. Al–TiC composites for various weight fractions (5, 10 and 15%) were fabricated by the salt route method using the reaction mixture of K_2TiF_6 and Gr powder with the molten metal. With the addition of TiC, wear rate increases initially and decreases with increase in weight percentage of TiC and the mechanical properties such as hardness and tensile strength of the composites enhanced than monolithic Al alloy (Jerome et al. 2010).

The secondary processing methods such as extrusion, cold drawing, and hot and cold rolling contribute to enhancement in mechanical properties and these improvements in properties are due to better interfacial attachment, grain size refinement and enhanced dispersion (Khanna et al. 2021). Micro- and nanosized boron nitride particles are added into AA 2219 through sintering process. The extrusion followed by sintering results in reduction in porosity and the extruded composites show superior mechanical properties compared to sintered composites (Rajkumar et al. 2022).

Stir-casting is the simplest and utmost economical method for the manufacturing of MMCs. The challenges in the stir-casting method include homogenous dispersal of the reinforcement particles in the matrix, unwanted chemical reactions, wettability issues, porosity and cluster or agglomeration formation. The main issue while dealing with nanocomposite through stir-casting method is the accomplishment of uniform distribution of nanosized particles. Great difference between the densities of nano sized particles and matrix alloy along with higher specific surface area of the nano particles resulted in poor wettability (Yuan et al. 2018). Due to poor wettability and higher surface tension of the particles, nanoreinforcements were floating over the surface. The bottom-type two-step stir-casting method, one of the advanced stir-casting methods, will give homogenous dispersion of particles but results in the small formation of clusters and agglomerations. Squeeze casting and ultrasonic cavitation-assisted stir-casting methods can be adopted for better dispersion and to reduce porosity, but these processes are not economical. During the casting process, the damage to the reinforcement particle is minimum, but there is less control in the reduction and particle size, and this can be reduced by the powder metallurgy process. Among the fabrication methods, powder metallurgy is the most preferred fabrication method which possess high strength, near net-shaped products, less scrap loss, uniform distribution of particles, and have low agglomeration tendency (Sharma et al. 2020). The advantages and disadvantages of stir-casting method and powder metallurgy are shown in Table 3.

Low-temperature processing method such as powder metallurgy is used for the manufacturing of nanocomposites, whereas high-temperature processing methods such as casting may lead to the formation of unwanted phase at

Table 3 Advantages, disadvantages and parameters of stir casting and powder metallurgy process

	Stir casting	Powder metallurgy
Advantages	High-temperature processing method Simple and economical method Simple operational procedures High production rate Continuous matrix media Suitable for low surface tension and low melting point materials	Low-temperature processing method Suitable for bulk manufacturing Near net-shaped products Better bonding of base material and reinforcement Better distribution of nanoparticles Enhances the mechanical properties by suppressing the grain growth
Disadvantages	Non-homogenous spreading of reinforcements in the base matrix Unwanted chemical reactions and oxidation problems Wettability issues Cluster or agglomeration formations Feebler bonding of matrix and nano reinforcements Large free zone of reinforcements Porosity issue Hinders the mechanical properties due to slow solidification resulting in higher grains Density mismatch between matrix and reinforcement results in floating of particles in the top of the composite	High complexity Discontinuous matrix media High porosity Suitable for high surface tension and high melting point materials
Parameters	Preheating temperature, stirring time and temperature, die temperature, melting temperature, particle size, feed rate of reinforcements, etc.	Particle size, compaction pressure, sintering time and temperature, process control agents (PCA), milling time, ball to powder ratio (BPR), holding time, etc.

interfaces. Microstructure conquered in the high-temperature processing method and slow solidification resulted in high grains that retard the mechanical properties, while in powder metallurgy method, it enhances the mechanical properties by suppressing the grain growth. Processing during the molten state has the benefit of production of bulk composites but is constrained by the non-wettability of the particles. Casting is appropriate for only amorphous structures, low melting point, and low surface tension material (below 200 mN/m). Most of the structural materials together with Al have high surface tension and have wetting contact angle above 90°, which is not appropriate for wetting. Difference in the surface tension of the materials results in poor wettability (Bakshi et al. 2010). Matrix grain size of the composites can be controlled by the powder metallurgy, and methods such as extrusion and rolling will shoot the physical properties by rearranging the reinforcement structures (Lloyd 1994). Multi-walled carbon nanotubes (MWCNTs) at 0.5 wt. % are reinforced in Al powder and fabricated through spark plasma sintering (SPS). The main issue in the processing of nanoparticles is the effect of van der Waals force and the formation of agglomerations and clusters. These clusters lead to the formation of pores or voids during the nanocomposite powder consolidation. High-energy ball milling technique is preferred to get homogenous dispersion of the reinforcements into the matrix and to avoid cluster or agglomeration formation (Manohar et al. 2021b). Ball milling process aids in lowering the activation energies of nanopowder particles by generating additional number of free surfaces, which is equal to increasing the sintering temperature (Lu et al. 1997). The electrical conductivity in all sintered samples improves by around 40% due to the effective multiwall carbon nanotubes (MWCNTs) network formed within the nanocomposite material that promotes electron transport (Ulloa-Castillo et al. 2021). CNT and Al_2O_3 were added into AA 6061 through stir-casting method and reported that at higher concentrations, agglomerations were developed and it is difficult to produce the composites at higher volumes (Prakash et al. 2021).

The end properties and interfacial bond strength of composites are highly influenced by the sintering temperatures. In conventional sintering method, sintering at higher temperatures resulted in the formation of unwanted intermetallic compounds. Studies reported that partial chemical reactions happen while sintering at moderate temperatures and intermetallic compounds are produced. These intermetallic compounds make a smoother way for effective load transfer. Therefore, choosing the appropriate sintering parameter is the main task in powder metallurgy. 6 vol. % B_4C is reinforced into AA 7075 by different sintering routes and results show that spark plasma-sintered composites show better properties along with low defects. Mechanical strength, ductility and porosity of AA 7075 reinforced with 6 vol. % B_4C under different sintering methods are shown in Fig. 12. Porosity formation is the main drawback of the PM composites; these porosities may be due to thermal mismatch between the matrix and reinforcement particles. In SPS composites, porosity level is comparatively lower than the conventional and microwave-sintered composites because

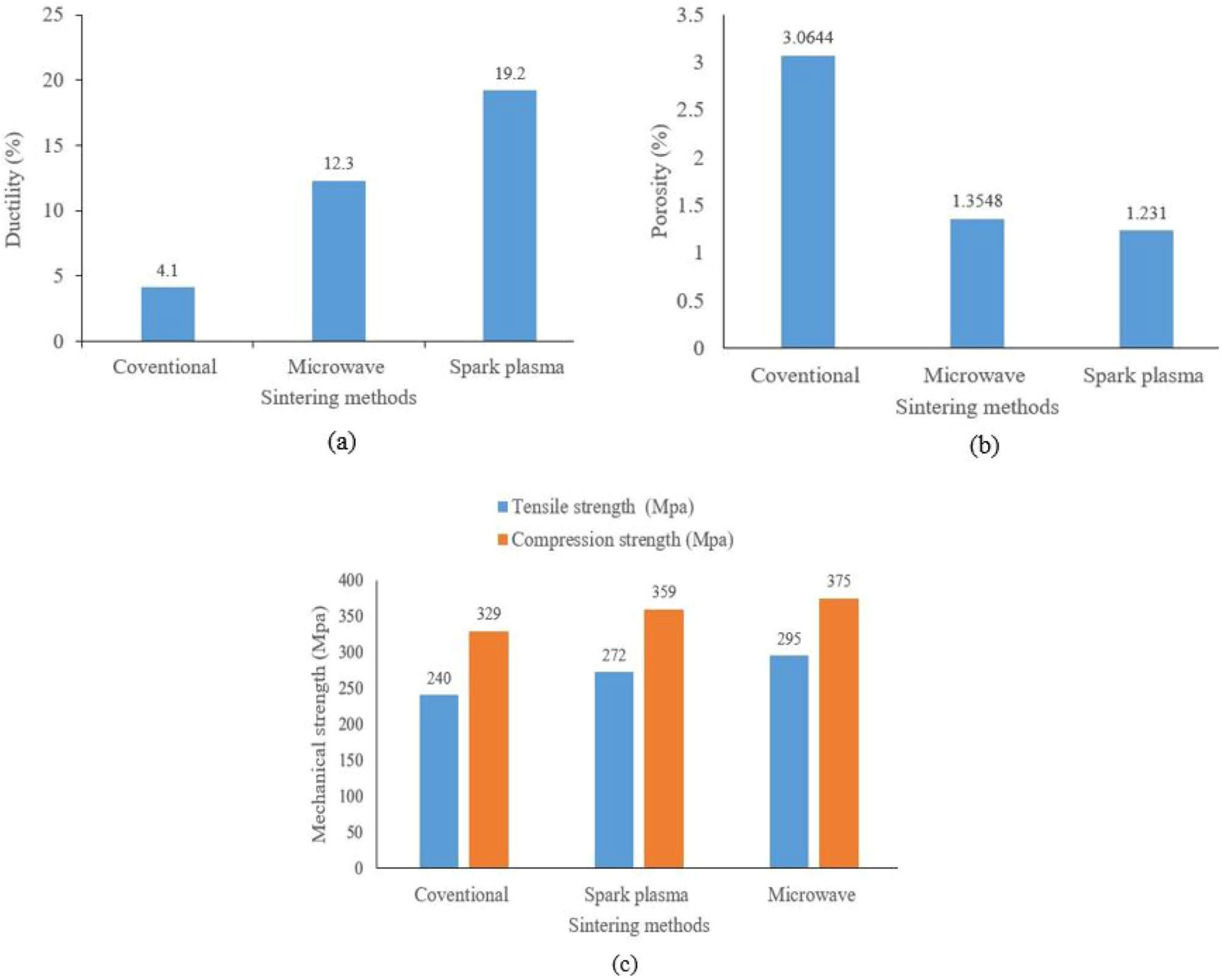


Fig. 12 Properties AA 7075 reinforced with 6 vol. % B_4C under different sintering methods (Manohar et al. 2021a)

of vacuum processing along with shorter heating period and faster diffusion process (Manohar et al. 2021a).

The processing of carbon fibres (C_f) through casting route is difficult, and due to their high-temperature processing, there may be a chance to damage the carbon fibres and formation of unwanted chemical reactions. Since the PM process controls the processing of carbon fibres to some amount, the conventional sintering method increases the risk of reaction between the C_f and AA. Spark plasma sintering empowers to process the bulk samples quickly with higher density at much lower sintering time and temperature, which reduces the reaction between the C_f and AA. Carbon fibres and ZrC_P were added into AA 2024 through spark plasma sintering method. Electroless Ni coating on $C_{f,}$ resulted in better interfacial bonding of fibres in the Al matrix. The strength and ductility of the AlMMCs can be improved together by incorporating multiscale and hybrid reinforcements (Xuan et al. 2021).

The mechanical properties such as density, yield, tensile and ultimate strength, hardness, and tribological properties such as wear rate and CoF for various base materials and reinforcements fabricated by different casting methods (Table 4) and powder metallurgy method (Table 5) are tabulated.

The literature supports that, in comparison to monolithic materials, the characteristics of metal matrix composites are superior. The property enhancement in MMCs is due to addition of different ceramic particles such as carbides, oxides, and nitrides, and carbon fibres. Among the different MMCs, AlMMCs are preferred than any other metal matrix composites due to its low density and high strength-to-weight ratio. AlMMCs have poor tribological performance at high temperatures and the studies reported that this can be compensated by adding the solid lubricants such as Gr, hBN, Si_3N_4, and MoS_2. The reinforcing particle size affects the composites strength and ductility. According to

Table 4 Mechanical and tribological properties of aluminium composites manufactured by different casting methods

Base matrix	Reinforcement and wt. %	Manufacturing method	Density, ρ (g/cc)	Strength (MPa)			Hardness	Wear rate	COF	Remarks	References
				σ_y	σ_t	σ_u					
Al–Si	–	Vortex casting	2.684		174		100 HV	2.03 mm^3/mm	0.148	Mechanical and tribological properties improved due Cr addition	Kumar et al. (2020)
	10 SiC		2.688		189		112 HV	1.36 mm^3/mm	0.114		
	10 SiC + 1.5 Cr		2.765		188		117 HV	1.14 mm^3/mm	0.146		
	10 SiC + 3 Cr		2.841		187		123 HV	0.793 mm^3/mm	0.170		
AA 7075	–	Stir casting	2.78		410		113 HV	0.0175 gms	0.23	Mechanical and tribological properties improved with Si_3N_4 addition	Haq et al. (2018)
	2 Si_3N_4		2.8		500		120 HV	0.012 gms	0.25		
	4 Si_3N_4		2.83		750		133 HV	0.008 gms	0.29		
	6 Si_3N_4		2.87		800		137 HV	0.007 gms	0.28		
	8 Si_3N_4		2.90		850		142 HV	0.006 gms	0.26		
AA 7075	–	Squeeze casting				175	109 HV			Mechanical properties improved	Agarwal et al. (2019)
	0.5 hBN + 1 Gr					190	113 HV				
AA 7075	–	Stir casting		65			122 HV			Mechanical properties are high when Gr particles are reinforced	Devaganesh et al. (2020)
	5 SiC + 5 Gr			247			176 HV				
	5 SiC + 5 hBN			199			120 HV				
	5 SiC + 5 MoS_2			137			137 HV				
AA 7075	–	Stir casting	8.5		470		181 VHN			Properties improved due to post-heat treatment	Veeravalli et al. (2016)
	2 TiC		8.2		550		189 VHN				
	4 TiC		7.9		568		193 VHN				
	6 TiC		7.6		583		197 VHN				
	8 TiC		7.2		600		202 VHN				
	10 TiC		7.5		583		195 VHN				
AA 6351	–	Stir casting					44 HV	1.55 mm^3/mm		Hardness increases and wear rate decreases	Ahamad et al. (2021)
	2.5 Al_2O_3 + 2.5 C						53 HV	1 mm^3/mm			
	5 Al_2O_3 + 5 C						55 HV	0.95 mm^3/mm			
	7.5 Al_2O_3 + 7.5 C						79 HV	0.9 mm^3/mm			
	10 Al_2O_3 + 10 C						94 HV	0.65 mm^3/mm			
AA 6061	–	Stir casting			283		74 BHN			Hardness, ultimate strength, impact strength increases	Mahaviradhan et al. (2021)
	5 C_f				304		85 BHN				
	10 C_f				315		92 BHN				
Pure Al	–	Squeeze casting		28		59	24 HV			Better tribological properties for hybrid composites	Mazaheri et al. (2013)
	10 TiB_2			66		115	44 HV	0.036 g	0.60		
	10 B_4C			75		132	51 HV	0.0225 g	0.50		
	5 B_4C + 5 TiB_2			72		123	55 HV	0.021 g	0.40		

Table 4 (continued)

Base matrix	Reinforcement and wt. %	Manufacturing method	Density, ρ (g/cc)	Strength (MPa)			Hardness	Wear rate	COF	Remarks	References
				σ_y	σ_t	σ_u					
Al 6082	–	Stir casting	2.7				52 HBN	0.7370 mm^3/m		Properties improved due to post-heat treatment	Kaushik and Rao (2016)
	10 SiC		2.8				67 HBN	0.5262 mm^3/m			
	5 SiC + 5 Gr		2.7				60 HBN	0.3964 mm^3/m			
Al 7075	–	Stir casting		451	360		60 HV			Mechanical properties enhanced	Chinmayee and Surekha (2021)
	6 TiC			310	350		62 HV				
	9 TiC			370	450		65 HV				
	12 TiC			220	245		60 HV				
	6 RM			225	175		172 HV				
	9 RM			125	140		153 HV				
	12 RM			80	120		143 HV				
Al 6351	–	Stir casting					44 HV	1.5210 $\text{mm}^{3/}$km		Hardness and wear resistance increase	Ahamad et al. (2021)
	2.5 Al_2O_3 + 2.5 TiO_2						49 HV	1.3214 $\text{mm}^{3/}$km			
	5 Al_2O_3 + 5 TiO_2						55 HV	1.1100 $\text{mm}^{3/}$km			
	7.5 Al_2O_3 + 7.5 TiO_2						68 HV	0.9814 $\text{mm}^{3/}$km			
	10 Al_2O_3 + 10 TiO_2						79 HV	0.8249 $\text{mm}^{3/}$km			
Al 6103	1 Al_2O_3	Stir casting					69 HRW	0.64 $\text{mm}^{3/}$km		Hardness and wear resistance increase	Hossain et al. (2020)
	1 Al_2O_3 + 2 SiC						71 HRW	0.24 $\text{mm}^{3/}$km			
	1 Al_2O_3 + 4 SiC						74 HRW	0.22 $\text{mm}^{3/}$km			
	1 Al_2O_3 + 6 SiC						79 HRW	0.17 $\text{mm}^{3/}$km			
	1 Al_2O_3 + 8 SiC						84 HRW	0.12 $\text{mm}^{3/}$km			
Cu	–	Stir casting	–	–	670	–	36.23 HBN	0.4508 mm^3/km		Strength and hardness increase along with wear resistance	Mittal et al. (2020)
	0.5 Al_2O_3 + 0.5 Gr		–	–	356	–	92.34 HBN	0.4121 mm^3/km			
	1 Al_2O_3 + 1 Gr		–	–	613	–	76.28 HBN	0.3989 mm^3/km			
	1.5 Al_2O_3 + 1.5 Gr		–	–	642	–	74.35 HBN	0.3221 mm^3/km			
	2 Al_2O_3 + 2 Gr		–	–	652	–	61.81 HBN	0.3110 mm^3/km			
AA 7075	–	Ultrasonic-assisted stir casting		146		223	84 BHN			Strength and hardness increases	Rao (2021)
	0.5 SiC_{np}			198		276	98 BHN				
	1 SiC_{np}			238		365	136 BHN				
	1.5 SiC_{np}			262		428	153 BHN				
	2 SiC_{np}			284		408	172 BHN				

Table 4 (continued)

Base matrix	Reinforcement and wt. %	Manufacturing method	Density, ρ (g/cc)	Strength (MPa)			Hardness	Wear rate	COF	Remarks	References
				σ_y	σ_t	σ_u					
AA 7075	–	Two-step stir casting	2.63				76 BHN	0.006 mm^3/km	0.4	Hardness and wear resistance increase for hBN addition	Rakshath et al. (2020)
	2.5 Al_2O_3		2.75				88 BHN	0.012 mm^3/km	0.51		
	5 Al_2O_3		2.77				95 BHN	0.022 mm^3/km	0.42		
	2.5 hBN		2.78				85 BHN	0.005 mm^3/km	0.32		
	5 hBN		2.71				91 BHN	0.007 mm^3/km	0.35		
AA 6061	1 Al_2O_3	Stir casting	2.71			127	44.52 HV			Agglomerations reported	Prakash et al. (2021)
	1 CNT		2.77			135	48.24 HV				
	1 CNT + 1 Al_2O_3		2.81			143	49.53 HV				
	1 CNT + 2 Al_2O_3		2.912			153	54.14 HV				

studies, when the particle size decreases from the micro- to nanoscale, the mechanical characteristics of the composites will be improved. To meet the current needs in the industry, AlMMCs are reinforced with two or more reinforcements to form the hybrid composites. The need of good quality, economical and performance-based materials has involved high attention of researchers in the composite materials. AlMMCs reinforced with bimodal-scaled reinforcement phases is the latest trends in the industry. Manufacturing of nanocomposite is one of the main tasks of the researches, and casting is preferred as the common approach for manufacturing of the composites. But in the case of nanocomposites, lot of challenges are being faced which includes cluster or agglomeration formation and non-wettability. For getting better dispersion of the nanoparticles in the matrix, powder metallurgy route is recommended.

Effect of post-heat treatment on Al alloys

Aluminium alloys are light-weight materials which are used in structural applications after proper heat treatment process. The influence of precipitation hardening and the effects of reinforcements have received less attention among the researchers, especially the studies related to the nanoreinforcements are very scarce. To attain the anticipated level of mechanical and tribological properties, Al alloys are exposed to heat treatment and work hardening. Heat treatment of Al alloys encompasses solutionizing, quenching, and ageing at room temperatures (natural ageing) or at elevated temperatures (artificial ageing). In precipitation hardening or age hardening, properties of alloys are improved because of the formation of extremely small and homogeneously distributed secondary phase particles within the phase matrix. The age hardening of the composites depends on the size, distribution, and coherency of precipitates formed. It has been observed that heat treatment does not completely change the morphology, but microstructures of precipitation-hardening alloys change during heat treatment (Sharma et al. 2009) which lead to improved hardness and strength. Most of the works reported that precipitation hardening or age hardening of the Al and alloys improves the mechanical properties of the Al alloy (Bhoi et al. 2020; Kumar et al. 2022).

MWCNT at 0.75 wt. % is added into AA 2219 and consolidated through spark plasma sintering method. The samples were exposed to T6 heat treatment by solutionizing at 535℃ for 70 min and then rapid cooled by quenching resulted in trapped Cu atoms at ambient temperature. After solutionizing, artificial ageing was carried out at 177℃ for 10 h. The T6 heat treatment of the samples is shown in Fig. 13. The work claims that the peak hardness is achieved in a short period of 90 min and enhanced the hardness by 82% when compared with that of sintering (hardness of sintered sample

Table 5 Mechanical and tribological properties of aluminium composites manufactured by different powder metallurgy methods

Base matrix	Reinforcement and wt. %	Manufacturing method	Density, ρ (g/cc)	Strength (M pa)			Hardness	Wear rate	COF	Remarks	References
				σ_y	σ_t	σ_u					
AA 7075	5% SiC	Powder metallurgy	2.81				64 HRB	3.9 mm^3	0.115	Wear loss and CoF decrease linearly with reinforcement addition	Surya and Gugulothu (2021)
	10% SiC		2.83				67 HRB	3.6 mm^3	0.096		
	15% SiC		2.85				70 HRB	2.5 mm^3	0.070		
Al 6061	10 SiC	Semi-solid powder densification (SSPD)					62 HV	0.09 g		Wear rate decreases with addition of Gr	Guo and Tsao (2000)
	10 SiC + 2 Gr						59 HV	0.38 g	0.38		
	10 SiC + 5 Gr						55 HV	1.09 g	0.5		
	10 SiC + 8 Gr						49 HV	0.71 g	0.28		
Mg	–	Powder metallurgy					29 HV	0.012 g	0.38	Better hardness, higher wear resistance and lower CoF than Mg	Narayanasamy et al. (2015)
	5 TiC						55 HV	0.008 g	0.4		
	5 MoS_2						35 HV	0.009 g	0.3		
	5 TiC + 5 MoS_2						59 HV	0.0075 g	0.4		
	10 TiC + 5 MoS_2						53 HV	0.007 g	0.16		
	5 TiC + 10 MoS_2						97 HV	0.007 g	0.14		
	10 TiC + 10 MoS_2						89 HV	0.0075 g	0.15		
Al	5 Al_2O_3	Powder metallurgy						0.020	0.517	Improvement in tribo-logical property for 5 Al_2O_3 + 5 MoS_2	Kanthavel et al. (2016)
	5 Al_2O_3 + 5 MoS_2							0.017	0.488		
	5 Al_2O_3 + 10 MoS_2							0.019			
AA 2014	–	Powder metallurgy						0.0013 mm^3/Nm		Better tribological property	Sundaram et al. (2021)
	5 Al_2O_3 + 5 TiB_2							0.0009 mm^3/Nm			
AA 7075	6 B_4C_{np}	Microwave sintering	2.762		402					Better mechanical properties compared to conventionally sintered composite	Manohar et al. (2021b)
	6 B_4C_{np} + 1 ZrC_{np}		2.795		452						
	6 B_4C_{np} + 2 ZrC_{np}		2.825		475						
	6 B_4C_{np} + 3 ZrC_{np}		2.864		502						
	6 B_4C_{np} + 4 ZrC_{np}		2.896		488						
	6 B_4C_{np} + 5 ZrC_{np}		2.926		469						
AA 2024	–	Powder metallurgy			245		86			Multi-scale reinforcement improves the strength and ductility	Xuan et al. (2021)
	1 ZrC_P				267		105				
	1 C_f				290		104				
	1 ZrC_P + 1 C_f				336		111				

Table 5 (continued)

Base matrix	Reinforcement and wt. %	Manufacturing method	Density, ρ (g/cc)	Strength (M pa)			Hardness	Wear rate	COF	Remarks	References
				σ_y	σ_t	σ_u					
AA 2219	–	Powder metallurgy	3		96					Mechanical properties improved up to 1.5 wt. % of nanoparticles	Rajkumar et al. (2022)
	9.5 BN_P + 0.5 BN_{np}		3.12		116						
	9 BN_P + 1 BN_{np}		3.15		270						
	8.5 BN_P + 1.5 BN_{np}		3.15		160						
	8 BN_P + 2 BN_{np}		3.15		124						
	7.5 BN_P + 2.5 BN_{np}		3.15		118						

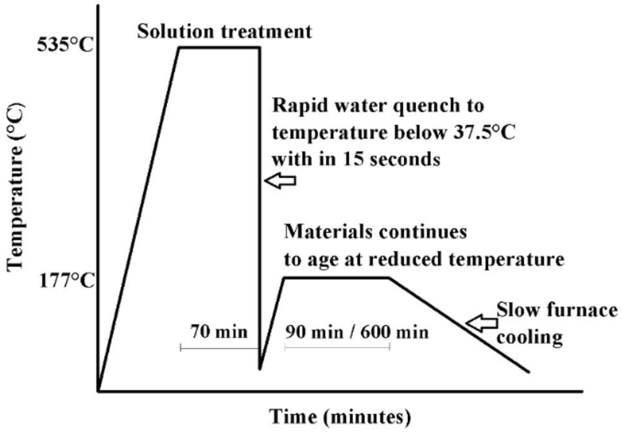


Fig. 13 AA 2219 + 0.75 wt. % of MWCNT composite subjected to T6 heat treatment and artificial ageing (Thomas 2018)

is 88 HV and hardness of 1.5 h aged sample is 160 HV) and AA 2219 achieved a development of 33% in peak hardness at 10 h of ageing. The improvement in hardness value for MWCNT has been reported due to the improved dislocation density because of the coefficient of thermal expansion mismatch among the AA 2219 and CNT's during solution heat treatment. The addition of MWCNTs in AA 2219 along with post-heat treatment resulted in improved material properties and achieving peak hardness in a short ageing period (Thomas and Umasankar 2019; Thomas 2018).

It is reported that the yield strength of the Al alloys and their composites increases after proper heat treatment due to the reduction of the cracking tendency and improvement of the precipitation hardening. Formerly, Al alloy composites are heat treated to an under-aged condition, as they can be shaped more easily and after the fabrication, these materials are heat treated to the peak-aged condition to enhance the mechanical properties. The heat-treated alloy and composites exhibit better hardness though the over-aged condition might incline the hardness significantly (Kumar et al. 2011).

AA 2219 was solution heat treated at 535℃ for 48 min followed by water quenched and then aged at 210℃, 230℃ and 240℃ for different time period. At 210℃ ageing temperature, the maximum UTS of 410 MPa is achieved after ageing for 4 h and after which the strength reduces to 352 MPa. The same samples when aged at 230℃ shows maximum UTS of 370 MPa at 3.5 h ageing and for 240℃ maximum UTS of 368 MPa at less ageing time of 1.5 h. The results show that the UTS increases up to peak-aged condition and then decreases due to over-aged condition; the increase in strength is due to the formation of precipitates. For the same samples, the maximum hardness is 113.76 HV obtained at ageing temperature 210 ℃ for ageing time of 4 h. Figure 14 shows the tensile strength and hardness of AA 2219 at different ageing temperatures 210℃, 230℃ and 240℃ for different

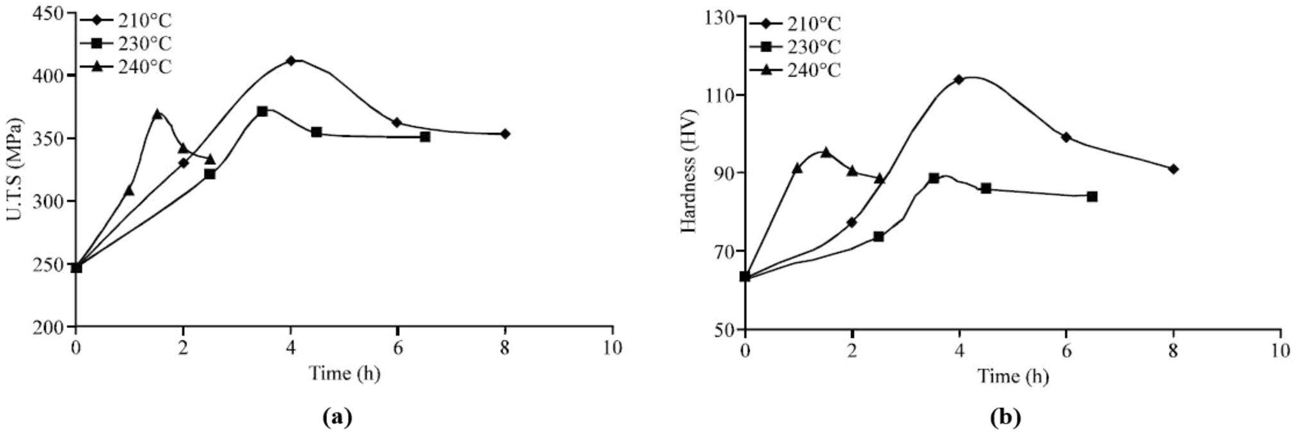


Fig. 14 Graphical representation of UTS and hardness versus ageing time at different ageing temperatures 210℃, 230℃ and 240℃ (Rafi Raza et al. 2011)

ageing times. The results show that at higher temperatures and increased ageing time, the maximum strength and hardness decreases (Rafi Raza et al. 2011).

AA 6061 + CNT composites were heat treated at 520℃ for 10 h and water quenched at ambient temperature. For proper dispersion of particles, sonication is done before wet ball milling. Annealing is done at 160℃ and 200℃ for 0.5, 1, 3, 6 and 10 h. At 160℃, unreinforced alloy attained peak hardness after 1 h, while at 200℃, peak hardness was achieved within 0.5 h. This difference is noted because at higher temperatures, the acceleration in the diffusion process resulted in formation of precipitates at the earliest. The same case happened for composites when it is subjected to age hardening. For composites, peak hardness was achieved at 3 h for 200℃ and for 160℃, peak hardness was achieved at 6 h. Due to the difference in the thermal properties of the reinforcement and matrix, inter-particle spacing is increased resulting in the lowering of hardness of nanocomposites than the unreinforced alloy for the ageing conditions. The work discusses that in some cases, the heat treatment of the composites will not enhance the properties when compared to the monolithic alloys (Saheb et al. 2013).

Al–Cu/CNT composite is prepared by spark plasma sintering method at a temperature of 500℃ for 5 min under a pressure of 50 bar. The powders were milled using a planetary mill for 3 h at 200 rpm and BPR 10:1. The composites were subjected to heat treatment and cold rolling. At 4 vol. % of CNT in Al–Cu matrix, hardness increases from 79.8 HV to 181.2 HV. After 3 h ageing, for the same composite composition, hardness enhanced to 193.8 HV. The results show that age hardening behaviours of the AlMMCs increased due to the excess dislocations formed by the mismatches in the coefficient of thermal expansion between the reinforcement and matrix (Nam, et al. 2012).

In another study, Al 6061 alloys are subjected to solution heat treatment at various temperatures (500℃, 540℃ and 580 ℃) and artificially aged at different temperatures (170℃, 200 ℃ and 230℃). The experiments suggest the suitable temperature for solution heat treatment of AA 6061 is 540℃ which yields better mechanical properties. Microstructure of these samples reveals that Mg_2Si is segregated in the annealed sample and at ageing temperature 170℃, fine grains of Mg_2Si phase are homogenously dispersed in the matrix. At 200℃, finely dispersed precipitates of Mg_2Si were observed. The microstructure of the sample at 230℃ showed the presence of coarse grains of Mg_2Si phase (Ataiwi et al. 2021). The microstructure of the annealed Al 6061 alloys under different ageing conditions is shown in Fig. 15. The tensile strength and yield stress are 290 MPa and 270 MPa, respectively, which is maximum at ageing temperature 200℃ for a ageing time of 6 h. For the same ageing time, the tensile strength and yield stress are 245 MPa and 215 MPa for a ageing temperature of 230℃ and for 170℃, the values are 240 MPa and 210 MPa. The enhancement in strength at ageing temperature 200℃ is due to the uniform dispersion and refinement of intermetallic compound Mg_2Si.

Al 7075 alloy reinforced with TiC ranges from 2 to 10 wt. %, and the composite is prepared by stir-casting method. The samples were subjected to heat treatment and aged at T6 condition. The material is homogenized at 450℃ for 2 h, and then aged at 121℃ for 24 h. For AA 7075 + 8 wt. % of TiC, the hardness of the cast and heat-treated samples improved from 98.4 VHN to 118.6 VHN and 181 VHN to 202.1 VHN. The wear rate decreases from 1.8 to 1.2 mm^3/kg, when the composite is subjected to heat treatment. It has been reported that the heat-treated composite has shown excellent enhancement in UTS, micro-hardness and wear

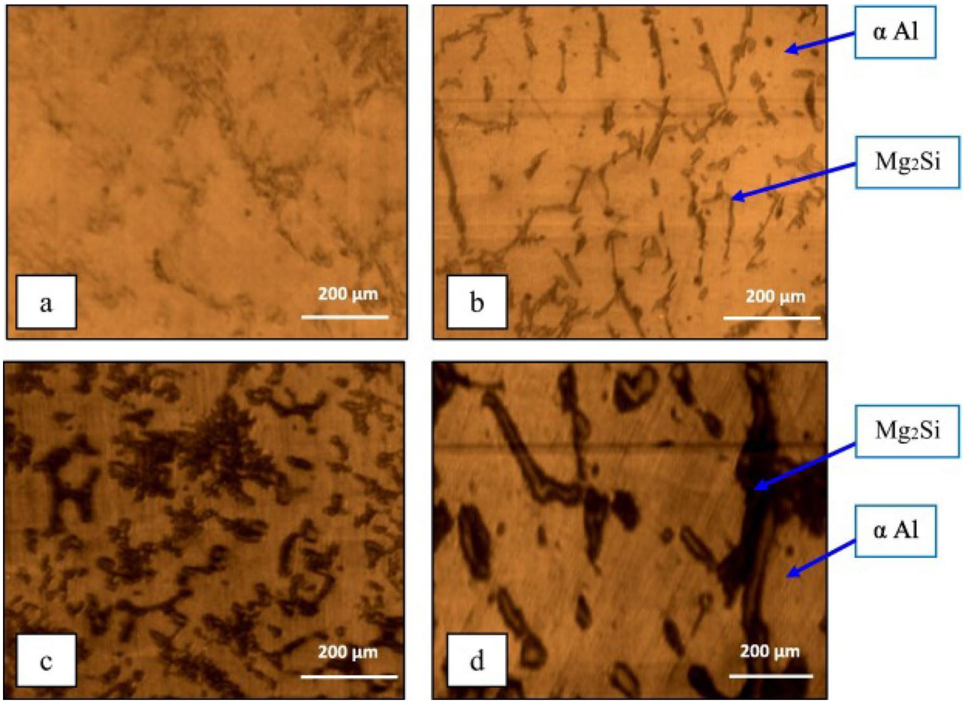


Fig. 15 Microstructure of AA 6061 **a** annealed AA 6061, **b** aged sample at 170℃, **c** aged sample at, 200℃, **d** aged sample at 230℃ (Ataiwi et al. 2021)

resistance than cast composites (Veeravalli et al. 2016). In another work, SiO_2 nanoparticles were added into Al matrix by stir-casting method and these samples were subjected to T6 heat treatment process—solutionizing at 500℃ for 5 h, water quenching and ageing 180℃ for 9 h. The results show that wear rate has improved for the heat-treated composites (Azadi et al. 2020).

Precipitation hardening or age hardening of aluminium and its alloys show that mechanical and tribological properties have improved compared with the untreated Al alloys. Maximum hardness is obtained at peak-aged condition due to the fine precipitate formation and at over-aged condition, intermediate phase begins to form causing recrystallization and thereby softening results in decrease in strength. The most suitable temperature for solution heat treatment of Al composites is between 530℃ and 540℃, which results in better homogenizing of α-Al phase for showing superior mechanical properties.

Conclusion

In this review paper, the different types of reinforcements along with their property changes and different production methods used in AlMMCs are described in detail. The main assumptions of this paper are briefed as follows.

- The choice of reinforcement selection is depending upon the end properties required. Nanosized particles have shown superior property enhancement than micron-sized particle reinforcement. The ceramic particulates such as silicon carbide (SiC), alumina (Al_2O_3), and boron carbide (B_4C) would significantly improve mechanical characteristics of the composites. But the addition of solid lubricants has a great potential to serve as secondary reinforcements resulting in superior mechanical and tribological properties.
- Low-temperature processing methods such as powder metallurgy are preferred than stir-casting method due to the ease control of microstructure, no interfacial reactions, non-wettability issues, low cluster or agglomeration formation, etc. The parameters of powder metallurgy includes ball milling time, milling speed, ball to powder ratio, ball diameter, process control agents (PCA), compaction pressure and time, sintering techniques, sintering temperature and sintering time
- Due to high surface energy and surface area of nanoreinforcements, it is difficult to manufacture the nanocomposites through high-temperature processing methods such as stir casting and squeeze casting. Powder metallurgy is one of the processing methods to manufacture the nanoreinforcements with the aid of advanced sintering techniques such as spark plasma sintering and microwave sintering.
- Fibre reinforcement in the matrix increases the load carrying capacity of the base material. Due to the difficult in processing of carbon fibres, it is rarely used in metal matrix composites. Powder metallurgy route along with low sintering time and temperature such as spark plasma sintering technique resulted in better material properties.

It is also reported that multiscale reinforcements establish higher strength and ductility.

- The post-heat treatment of Al composites mostly results in better mechanical properties and wear resistance. Maximum hardness is obtained at peak-aged condition due to the fine precipitate formation, and at over-aged condition, intermediate phase begins to form recrystallization and thereby softening results in decrease in strength. The increase in wear resistance is due to formation of intermetallic precipitates during ageing process
- The most suitable temperature for solution heat treatment of Al composites is between 530℃ and 540℃, which results in better homogenizing of α-Al phase for showing superior mechanical properties. At higher temperatures and increased ageing time, the maximum strength and hardness decrease.
- Carbon reinforcements in Al alloys and their proper heat treatment will enhance the structural and functional properties of the composites which enable them to be used in aerospace and automobile industries.

Future scope

Fewer studies are reported which reinforces solid lubricants and fibres in aluminium metal matrix composites. Hybrid nano composites will be the best options for structural applications because the addition of solid lubricants to AlMMCs will increase the tribological characteristics and the reduction in the mechanical properties may be made up by reinforcing the fibres. Since uniform dispersion of nanoparticles through casting approach is challenging to be obtained, the majority of works relating to AlMMCs employ this method. The best technique for creating nanocomposites employs powder metallurgy route in conjunction with contemporary sintering techniques such as microwave sintering and spark plasma sintering.

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Data availability No data available.

Ethics

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

Ethical approval This article does not contain any studies with human participants or animals performed by any of the authors.

References

Agarwal P, Kishore A, Kumar V, Soni SK, Thomas B (2019) Fabrication and machinability analysis of squeeze cast Al 7075/h-BN/graphene hybrid nanocomposite. Eng Res Expr 1(1):015004. https://doi.org/10.1088/2631-8695/ab26f5

Ahamad N, Mohammad A, Gupta P (2021) Wear characteristics of Al matrix reinforced with Al_2O_3-carbon hybrid metal matrix composites. Mater Today Proc 38:63–68

Akbari MK, Baharvandi HR, Shirvanimoghaddam K (2015) Tensile and fracture behavior of nano/micro TiB_2 particle reinforced casting A356 aluminum alloy composites. Mater Des 66:150–161

Alten A et al (2019) Production and mechanical characterization of Ni-coated carbon fibers reinforced Al-6063 alloy matrix composites. J Alloys Compd 787:543–550

Amirkhanlou S, Niroumand B (2010) Synthesis and characterization of 356-SiC_p composites by stir casting and compocasting methods. Trans Nonferrous Metals Soc China 20:s788–s793

Ashwath P, Xavior MA (2018) Effect of ceramic reinforcements on microwave sintered metal matrix composites. Mater Manuf Process 33(1):7–12

Assadi H et al (2016) Cold spraying–a materials perspective. Acta Mater 116:382–407

Ataiwi AH, Dawood JJ, Madhloom MA (2021) Effect of precipitation hardening treatments on tensile properties, impact toughness, and microstructural changes of aluminum alloy AA6061. Mater Today Proc. https://doi.org/10.1016/j.matpr.2021.06.011

Auradi V, Rajesh GL, Kori SA (2014) Preparation and evaluation of mechanical properties of 6061Al–B4C_p composites produced via two-stage melt stirring. Mater Manuf Processes 29(2):194–200

Azadi M et al (2020) Investigation of tribological and compressive behaviors of Al/SiO_2 nanocomposites after T6 heat treatment. Sādhanā 45(1):1–13

Bahl S (2021) Fiber reinforced metal matrix composites-a review. Mater Today Proc 39:317–323

Bakshi SR, Lahiri D, Agarwal A (2010) Carbon nanotube reinforced metal matrix composites-a review. Int Mater Rev 55(1):41–64

Bhoi NK, Singh H, Pratap S (2020) Developments in the aluminum metal matrix composites reinforced by micro/nano particles–a review. J Compos Mater 54(6):813–833

Cabeza M et al (2017) Effect of high energy ball milling on the morphology, microstructure and properties of nano-sized TiC particle-reinforced 6005A aluminium alloy matrix composite. Powder Technol 321:31–43

Canakci A, Varol T (2015) A novel method for the production of metal powders without conventional atomization process. J Clean Prod 99:312–319

Chand S (2000) Review carbon fibers for composites. J Mater Sci 35(6):1303–1313

Chandel R, Sharma N, Bansal S (2021) A review on recent developments of aluminum-based hybrid composites for automotive applications. Emergent Mater 4(5):1243–1257. https://doi.org/10.1007/s42247-021-00186-6

Chawla N, Shen Y-L (2001) Mechanical behavior of particle reinforced metal matrix composites. Adv Eng Mater 3(6):357–370

Chinmayee K, Surekha B (2021) Characterisation of aluminium metal matrix composites reinforced with titanium carbide and red mud. Mater Res Innov 25(2):67–75

Czerwinski F (2020) Thermal stability of aluminum alloys. Materials 13(15):3441

Dai Q, Kelly J, Elgowainy A (2016) Vehicle materials: material composition of US light-duty vehicles. In: Energy systems division. Argonne National Labs, Chicago, p 1–30

Deepanraj B, Senthilkumar N, Tamizharasan T (2021) Sintering parameters consequence on microstructure and hardness of copper alloy prepared by powder metallurgy. Mater Today Proc. https://doi.org/10.1016/j.matpr.2021.06.389

Devaganesh S, Venkatesh N, Kumar PKD (2020) Investigation on influence of solid lubricants over mechanical behavior of hybrid Al7075-SiC metal matrix composites. Mater Today Proc 27:2864–2869

Domnich V et al (2011) Boron carbide: structure, properties, and stability under stress. J Am Ceram Soc 94(11):3605–3628

Esawi AMK et al (2011) The influence of carbon nanotube (CNT) morphology and diameter on the processing and properties of CNT-reinforced aluminium composites. Compos A Appl Sci Manuf 42(3):234–243

Faisal N, Kumar K (2018) Mechanical and tribological behaviour of nano scaled silicon carbide reinforced aluminium composites. J Exp Nanosci 13(sup1):S1–S13

Fei C et al (2015) Microstructure, mechanical properties and wear behaviour of Zn–Al–Cu–TiB_2 in situ composites. Trans Nonferrous Metals Soc China 25(1):103–111

Frank E, Hermanutz F, Buchmeiser MR (2012) Carbon fibers: precursors, manufacturing, and properties. Macromol Mater Eng 297(6):493–501

Guo MLT, Tsao CYA (2000) Tribological behavior of self-lubricating aluminium/SiC/graphite hybrid composites synthesized by the semi-solid powder-densification method. Compos Sci Technol 60(1):65–74

Gupta N, Luong DD, Cho K (2012) Magnesium matrix composite foams—density, mechanical properties, and applications. Metals 2(3):238–252

Gurusamy P, Prabu SB (2013) Effect of the squeeze pressure on the mechanical properties of the squeeze cast Al/SiC_p metal matrix composite. Int J Microstruct Mater Prop 8(4–5):299–312

Haghshenas M (2016) Metal–matrix composites. Elseiver

Haq Ul, Irfan M, Anand A (2018) Dry sliding friction and wear behavior of AA7075-Si3N4 composite. SILICON 10(5):1819–1829

Hossain S et al (2020) Fabrication, microstructural and mechanical behavior of Al-Al_2O_3-SiC hybrid metal matrix composites. Mater Today Proc 21:1458–1461

Hussain S et al (2020) Fe_3O_4 nanoparticles decorated multi-walled carbon nanotubes based magnetic nanofluid for heat transfer application. Mater Lett 274:128043

Idrisi AH, Mourad A-HI (2019) Conventional stir casting versus ultrasonic assisted stir casting process: mechanical and physical characteristics of AMCs. J Alloys Compd 805:502–508

Jerome S et al (2010) Synthesis and evaluation of mechanical and high temperature tribological properties of in-situ Al–TiC composites. Tribol Int 43(11):2029–2036

Kainer KU (2006) Basics of metal matrix composites. Metal matrix composites: custom-made materials for automotive and aerospace engineering. WILEY VCH & CO. KgaA, Weinhelm, pp 1–54

Kannan C, Ramanujam R (2017) Comparative study on the mechanical and microstructural characterisation of AA 7075 nano and hybrid nanocomposites produced by stir and squeeze casting. J Adv Res 8(4):309–319

Kanthavel K, Sumesh KR, Saravanakumar P (2016) Study of tribological properties on Al/Al2O3/MoS2 hybrid composite processed by powder metallurgy. Alex Eng J 55(1):13–17

Kaushik NCH, Rao RN (2016) The effect of wear parameters and heat treatment on two body abrasive wear of Al–SiC–Gr hybrid composites. Tribol Int 96:184–190

Kazakov NF (ed) (1985) Diffusion bonding of materials. Elsevier. https://doi.org/10.1016/C2013-0-03774-7

Khanna V, Kumar V, Bansal SA (2021) Mechanical properties of aluminium-graphene/carbon nanotubes (CNTs) metal matrix composites: Advancement, opportunities and perspective. Mater Res Bull 138:111224

Kim KK, Kim SM, Lee YH (2014) A new horizon for hexagonal boron nitride film. J Korean Phys Soc 64(10):1605–1616

Kumar UKGBAV (2017) Method of stir casting of aluminum metal matrix composites: a review. Mater Today Proc 4(2):1140–1146

Kumar GBV, Rao CSP, Selvaraj N (2011) Mechanical and tribological behavior of particulate reinforced aluminum metal matrix composites–a review. J Miner Mater Charact Eng 10(01):59–91

Kumar PN, Rajadurai A, Muthuramalingam T (2018) Multi-response optimization on mechanical properties of silica fly ash filled polyester composites using taguchi-grey relational analysis. SILICON 10(4):1723–1729

Kumar J et al (2020) Comparative study on the mechanical, tribological, morphological and structural properties of vortex casting processed, Al–SiC–Cr hybrid metal matrix composites for high strength wear-resistant applications: fabrication and characterizations. J Mater Res Technol 9(6):13607–13615

Kumar PL et al (2022) Recent advances in aluminium matrix composites reinforced with graphene-based nanomaterial: a critical review. Prog Mater Sci. https://doi.org/10.1016/j.pmatsci.2022.100948

Labib F, Mahmudi R, Ghasemi HM (2018) High-temperature mechanical properties of the P/M Extruded Mg-SiC_p composites. J Mater Eng Perform 27(3):1224–1231

Li B et al (2017) Effect of TiN nanoparticles on microstructure and properties of Al2024-TiN nanocomposite by high energy milling and spark plasma sintering. J Alloys Compd 726:638–650

Liu K, Chen X-G (2015) Development of Al–Mn–Mg 3004 alloy for applications at elevated temperature via dispersoid strengthening. Mater Des 84:340–350

Lloyd DJ (1994) Particle reinforced aluminium and magnesium matrix composites. Int Mater Rev 39(1):1–23

Loganathan P, Gnanavelbabu A, Rajkumar K (2021) Influence of ZrB_2/hBN particles on the wear behaviour of AA7075 composites fabricated through stir followed by squeeze cast technique. Proc Inst Mech Eng J J Eng Tribol 235(1):149–160

Lu L, Lai MO, Zhang S (1997) Diffusion in mechanical alloying. J Mater Process Technol 67(1–3):100–104

Mahaviradhan N et al (2021) Experimental investigation on mechanical properties of carbon fiber reinforced aluminum metal matrix composite. Mater Today Proc 39:743–747

Maleki A, Niroumand B, Shafyei A (2006) Effects of squeeze casting parameters on density, macrostructure and hardness of LM13 alloy. Mater Sci Eng A 428(1–2):135–140

Mamedov V (2002) Spark plasma sintering as advanced PM sintering method. Powder Metall 45(4):322–328

Manohar G et al. (2018) Fabrication of metal matrix composites by powder metallurgy: a review. In: AIP conference proceedings, vol 1952. AIP Publishing LLC, p 020041

Manohar G, Pandey KM, Maity SR (2021a) Effect of sintering mechanisms on mechanical properties of AA7075/B4C composite fabricated by powder metallurgy techniques. Ceram Int 47(11):15147–15154

Manohar G, Pandey KM, Maity SR (2021b) Effect of microwave sintering on the microstructure and mechanical properties of AA7075/B4C/ZrC hybrid nano composite fabricated by powder metallurgy techniques. Ceram Int 47(23):32610–32618

Mattli MR et al (2019) Structural and mechanical properties of amorphous Si_3N_4 nanoparticles reinforced Al matrix composites prepared by microwave sintering. Ceramics 2(1):126–134

Mattli MR et al (2021) Study of microstructural and mechanical properties of Al/SiC/TiO_2 hybrid nanocomposites developed by microwave sintering. Crystals 11(9):1078

Mavhungu ST et al (2017) Aluminum matrix composites for industrial use: advances and trends. Procedia Manuf 7:178–182

Mazaheri Y et al (2013) Comparison of microstructural and mechanical properties of Al–TiC, Al–B_4C and Al–TiC–B_4C composites prepared by casting techniques. Mater Sci Eng A 560:278–287

Menachery N, CV Biju, MT Sijo. (2013) Investigation of mechanical properties and grain structure of 5xxx aluminium alloys under precisely controlled annealed conditions. Int J Sci Res Publ 3(1)

Mendoza-Duarte JM et al (2015) Study of Al composites prepared by high-energy ball milling; Effect of processing conditions. J Alloy Compd 643:S172–S177

Miller WS et al (2000) Recent development in aluminium alloys for the automotive industry. Mater Sci Eng A 280(1):37–49

Mishra RS, Ma ZY, Charit I (2003) Friction stir processing: a novel technique for fabrication of surface composite. Mater Sci Eng A 341(1–2):307–310

Mittal P et al (2020) Structural, wear and thermal behaviour of Cu–Al_2O_3–graphite hybrid metal matrix composites. Proc. Inst. Mech. Eng. L 234(8):1154–1164

Moghadam AD et al (2015) Mechanical and tribological properties of self-lubricating metal matrix nanocomposites reinforced by carbon nanotubes (CNTs) and graphene–a review. Compos B Eng 77:402–420

Moona G et al (2018) Aluminium metal matrix composites: a retrospective investigation. IJPAP 56(2):164–175

Mu DKQ et al (2021) The microstructures and mechanical properties of a 5vol% SiC/AA2024 nanocomposite fabricated by powder metallurgy. Mater Charact 175:111090

Mu W et al (2022) Fabrication of continuous carbon-fibers reinforced aluminum matrix composites and coating evolution during heat treatment. J Mater Res Technol 17:1852–1867

Munro RG (2000) Material properties of titanium diboride. J Res Natl Inst Stand Technol 105(5):709

Nam DH et al (2012) Effect of CNTs on precipitation hardening behavior of CNT/Al–Cu composites. Carbon 50(13):4809–4814

Namini AS et al (2021) Spark plasma sinterability of TiC ceramics with different nitride additives. J Taiwan Inst Chem Eng 123:363–370

Narayanasamy P, Selvakumar N, Balasundar P (2015) Effect of hybridizing MoS2 on the tribological behaviour of Mg–TiC composites. Trans Indian Inst Met 68(5):911–925

Naseem A et al (2021) Wear, optimization and surface analysis of Al-Al2O3-TiO2 hybrid metal matrix composites. Proc Inst Mech Eng Part J 235(1):93–102

Pakdel A et al (2017) A comprehensive microstructural analysis of Al–WC micro-and nano-composites prepared by spark plasma sintering. Mater Des 119:225–234

Parakh A et al (2019) Fabrication and machinability analysis of squeeze cast Al 7075/h-BN/graphene hybrid nanocomposite. Eng Res Expr 1(1):015004

Pensl G et al (2005) SiC material properties. Int J High Speed Electron Syst 15(04):705–745

Podgornik B et al (2015) Tribological behaviour and lubrication performance of hexagonal boron nitride (h-BN) as a replacement for graphite in aluminium forming. Tribol Int 81:267–275

Popov VN (2004) Carbon nanotubes: properties and application. Mater Sci Eng R Rep 43(3):61–102

Pradeep Kumar GS et al (2021) Studies on parametric optimization of HVOF-sprayed Cr_2O_3 coatings on Al6061 alloy. Trans Indian Inst Met 74(8):2013–2025

Prakash DS et al (2021) Experimental investigation of nano reinforced aluminium based metal matrix composites. Mater Today Proc 54:852–857

Prasad SV, Asthana R (2004) Aluminum metal-matrix composites for automotive applications: tribological considerations. Tribol Lett 17(3):445–453

Raj P, Biju PL, Deepanraj B et al (2022) A systematic review on characterization of hybrid aluminium nanocomposites. Mater Today Proc. https://doi.org/10.1016/j.matpr.2022.08.236

Rajak DK et al (2019) Recent progress of reinforcement materials: a comprehensive overview of composite materials. J Mater Res Technol 8(6):6354–6374

Rajkumar S et al (2022) Physical and mechanical properties of AA2219/BN composites. Mater Today Proc. https://doi.org/10.1016/j.matpr.2021.12.116

Rakshath S et al (2020) Dry sliding and abrasive wear behaviour of Al-7075 reinforced with alumina and boron nitride particulates. Mater Today Proc 22:619–626

Rana V, Kumar H, Kumar A (2022) Fabrication of hybrid metal matrix composites (HMMCs)–a review of comprehensive research studies. Mater Today Proc. https://doi.org/10.1016/j.matpr.2021.12.241

Rao TB (2021) Microstructural, mechanical, and wear properties characterization and strengthening mechanisms of Al7075/SiCnp composites processed through ultrasonic cavitation assisted stir-casting. Mater Sci Eng A 805:140553

Rafi Raza M, Ahmad F, Ikram N, Ahmad R, Salam A (2011) Development and strengthening of 2219 aluminium alloy by mechanical working and heat treatment. J Appl Sci 11(10):1857–1861

Reddy MP et al (2017) Enhanced performance of nano-sized SiC reinforced Al metal matrix nanocomposites synthesized through microwave sintering and hot extrusion techniques. Prog Nat Sci 27(5):606–614

Riley FL (2000) Silicon nitride and related materials. J Am Ceram Soc 83(2):245–265

Saheb N et al (2013) Age hardening behavior of carbon nanotube reinforced aluminum nanocomposites. J Nano Res 21:29–35

Sajjadi SA, Ezatpour HR, Parizi MT (2012) Comparison of microstructure and mechanical properties of A356 aluminum alloy/Al_2O_3 composites fabricated by stir and compo-casting processes. Mater Des 34:106–111

Sharma A, Jae PJ (2017) Possibility of Al-Si brazing alloys for industrial microjoining applications. J Microelectron Packag Soc 24(3):35–40

Sharma VMJ et al (2009) Studies on the work-hardening behavior of AA2219 under different aging treatments. Metall and Mater Trans A 40(13):3186–3195

Sharma P, Khanduja D, Sharma S (2015) Production of hybrid composite by a novel process and its physical comparison with single reinforced composites. Mater Today Proc 2(4–5):2698–2707

Sharma DK, Mahant D, Upadhyay G (2020) Manufacturing of metal matrix composites: a state of review. Mater Today Proc 26:506–519

Singh N, Belokar RM (2021) Tribological behavior of aluminum and magnesium-based hybrid metal matrix composites: a state-of-art review. Mater Today Proc 44:460–466

Singh K et al (2021) Mechanical study of Al 7050 and Al 7075 based metal matrix composites: a review. Mater Today Proc 43:673–677

Slipenyuk A et al (2004) The effect of matrix to reinforcement particle size ratio (PSR) on the microstructure and mechanical properties of a P/M processed AlCuMn/SiC_p MMC. Mater Sci Eng, A 381(1–2):165–170

Starke EA Jr, Staley JT (1996) Application of modern aluminum alloys to aircraft. Prog Aerosp Sci 32(2–3):131–172

Stojanovic B, Igor E (2018) Application of aluminum and aluminum alloys in engineering. Appl Eng Lett. https://doi.org/10.18485/aeletters.2018.3.2.2

Sundaram J, Prakash JU, Kagitha H (2021) Wear properties on AA2014/Al 2 O 3/TiB 2 hybrid metal matrix composites. Innovative design, analysis and development practices in aerospace and automotive engineering. Springer, Singapore, pp 389–395

Surya MS, Gugulothu SK (2021) Fabrication, mechanical and wear characterization of silicon carbide reinforced aluminium 7075 metal matrix composite. SILICON. https://doi.org/10.1007/s12633-021-00992-x

Tabandeh-Khorshid M et al (2016) Tribological performance of self-lubricating aluminum matrix nanocomposites: role of graphene nanoplatelets. Eng Sci Technol Int J 19(1):463–469

Thevenot F (1990) Boron carbide—a comprehensive review. J Eur Ceram Soc 6(4):205–225

Thomas S (2018) Effect of MWCNT reinforcement on the precipitation-hardening behavior of AA2219. Int J Miner Metall Mater 25(1):53–61

Thomas S (2021) Effect of a novel sintering technique: hot coining on microstructure and mechanical properties of MWCNT reinforced Al metal matrix nanocomposite. Adv Mater Process Technol. https://doi.org/10.1080/2374068X.2021.1970999

Thomas S, Umasankar V (2019) Review of recent progress in the development and properties of aluminum metal matrix composites reinforced with multiwalled carbon nanotube by powder metallurgy route. Mater Perform Charact 8(3):371–400

Thomas S et al (2019a) Self lubricating property of MWCNT in AA2219 composites during high energy ball milling. Mater Today Proc 18:3387–3393

Thomas S et al (2019b) Effect of sonication in enhancing the uniformity of MWCNT distribution in aluminium alloy AA2219 matrix. Mater Today Proc 18:4058–4066

Thomas S et al (2020) An improved compocasting technique for uniformly dispersed multi-walled carbon nanotube in AA2219 alloy melt. FME Trans 48(3):581–587

Thomas S, Tom P, Umasankar V (2020) Effect of MWCNT concentration on microstructures, mechanical properties and sintering behaviour of spark plasma sintered AA2219-MWCNT composites. Mater Today Proc 22:1424–1432

Tjong SC (2013) Recent progress in the development and properties of novel metal matrix nanocomposites reinforced with carbon nanotubes and graphene nanosheets. Mater Sci Eng R Rep 74(10):281–350

Ulloa-Castillo NA et al (2021) Enhancement of electrical conductivity of aluminum-based nanocomposite produced by spark plasma sintering. Nanomaterials 11(5):1150

Umasankar V, Shijo T (2018) Influence of manufacturing process on distribution of MWCNT in aluminium alloy matrix and its effect on microhardness. Mater Sci Forum 928:32–37

Vani VV, Sanjay KC (2018) The effect of process parameters in aluminum metal matrix composites with powder metallurgy. Manuf Rev 5:7

Varol T, Canakci A (2013) Effect of particle size and ratio of B4C reinforcement on properties and morphology of nanocrystalline Al2024-B4C composite powders. Powder Technol 246:462–472

Vassel A (1999) Continuous fibre reinforced titanium and aluminium composites: a comparison. Mater Sci Eng A 263(2):305–313

Veeravalli RR, Nallu R, Mohiuddin SMM (2016) Mechanical and tribological properties of AA7075–TiC metal matrix composites under heat treated (T6) and cast conditions. J Mater Res Technol 5(4):377–383

Viala JC et al (1997) Chemical reactivity of aluminium with boron carbide. J Mater Sci 32(17):4559–4573

Viswanatha BM et al (2013) Mechanical property evaluation of A356/SiC$_p$/Gr metal matrix composites. J Eng Sci Technol 8(6):754–763

Warren AS (2004) Developments and challenges for aluminum–a boeing perspective. Mater Forum 28:24–31

Xuan Z et al (2021) Fabrication and characteristic of 2024Al matrix composites reinforced by carbon fibers and ZrC$_p$ by spark plasma sintering. J Alloys Compd 889:161543

Yuan D et al (2018) Preparation and properties of nano-SiC$_p$/A356 composites synthesised with a new process. Mater Sci Technol 34(12):1415–1424