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Review Article

Advance research progresses in aluminium matrix composites: manufacturing & applications

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ABSTRACT

At present aluminium matrix composites are widely used in engineering applications. Aluminium matrix composites are providing such superior properties which cannot be achieved by any existing monolithic material. Properties of aluminium matrix composite are highly influenced by nature of reinforcement which can be either in continuous or discontinuous fibre form. It also depends on the selection of processing techniques for the fabrication of aluminium matrix composites which depends on many factors including type of matrix and reinforcement, the degree of microstructural integrity desired and their structural, mechanical, electrochemical and thermal properties. Present paper reports an overview on synthesis routes, mechanical behavior and applications of aluminium matrix composites. Special focus is given to primary processing techniques for manufacturing of aluminium matrix composites. In the end, commercialization challenges, industrial aspects and future research directions are also briefed.

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1. Introduction

At present aluminium matrix composites are highly demanding material in aerospace industry, automobile industry and other engineering applications. Aluminium matrix composites find a wide range of popularity in transportation sector because of lower noise and lower fuel consumptions over another material. Composite materials are old as our human civilization but commercialized after 2nd world war. A composite is a material that consists of constituents produced by a physical combination of pre-existing monolithic compounds to obtain a new material with unique properties when compared to the base composition. Current definition distinguishes a composite from other multiphase materials which are produced by bulk processes where one or more phases result from phase transformation. In general, two phases are present in any composite (a) matrix and (b) reinforcement. Composite is defined as a material which consists of two or more physically and chemically distinct parts which are suitably arranged and are having different properties with respect to those of each constituent part [1]. Industry and material scientist define composite as a material that consists of constituents produced by a physical combination of already existing compound to yield a new material with different properties as compared to the base composition. In general matrix is continuous and surrounds the discontinuous reinforcement phase present in the composite material. The composites are classified according to: (1) their matrix (polymer, ceramic, metal and carbon) (2) their reinforcement, which includes their chemical nature (oxides, carbides and nitrides), (3) the shape (continuous fibres, short fibres, whiskers and particulates) and (4) the orientation and (5) the processing routes [2]. The other two classes are (d) carbon–carbon composites and (e) hybrid matrix composites. In a composite, when the matrix is a metal or an alloy of metal, we have a metal matrix composite (MMC), which forms the percolating network. Other constituent embedded in this metal/metal alloy matrix serves as reinforcement. It is usually non-metallic and are commonly ceramic such as SiC, C, Al_2O_3, SiO_2, B, BN, B_4C, AlN [3].

Many factors influence the selection of the processing technique, which include the type of reinforcement and matrix, their mechanical and thermal properties and the extent of microstructural integrity desired. The type of reinforcement, variation of reinforcement in matrix and interaction of matrix with reinforcement plays a vital role in determining the final properties of the composite [4]. Various investigations have been carried out using the different type of matrix materials [5].

Magnesium based composites has gained a lot of attention due to improved mechanical and corrosion properties. It serves as a potential candidate for application in light weight components. Most Mg–Al alloys contain 8–9% Al with small amount of Zn to give increase in tensile strength. 0.1–0.3 wt% addition of Mn improves corrosion resistance. Composite materials based on Mg alloys reinforced by dispersion particles of silicon carbide (SiC) shows very low density in the range of 2.0–2.1 g/cm^3 and are characterized by 30–40% better mechanical properties than unreinforced magnesium alloys. High reactivity of Mg leads to significant problems in synthesis of Mg-based MMCs. Improper fabrication process can also cause degradation rather than improvement of the mechanical properties. Thus, special attention should be given to the reaction products at the interface between SiC particles and the Mg matrix.

Iron based metal matrix composites are used for heavy duty applications such as railway wagon wheels, braking system etc. Synthesis of iron based composites is carried out using powder metallurgy technique since it leads to the generation of homogenous phase along with least interaction between the matrix and reinforcement phase. Gupta et al. reported that for Fe-Al_2O_3 metal matrix composites the various properties such as density, hardness, wear, deformation and corrosion is found to improve. Improvement in the properties is found due to iron aluminate ($FeAl_2O_4$) phase formation. Iron aluminate phase forms as a result of reactive sintering between iron and alumina particles [6–10].

Micrometric Al_2O_3 particulates have been widely used in aluminium matrix composites, and some literature on use of nano-metric Al_2O_3 particulates are also available [11,12]. Aluminium and its alloys are one of the most widely used light weight materials in MMCs as matrix, both from research and industrial point of view. This is attributed to its outstanding properties, such as high strength, high specific modulus, good wear resistance and low thermal expansion coefficient [13,14].

Bandil et al. [15] investigated the effect of SiC reinforcement on Al-Si alloy properties. Composites were fabricated by stir casting process. It is reported that density of composites decreases with increase in SiC content. Hardness of composites also increases as increase in SiC content due to hard nature and uniform distribution of SiC particles in Al matrix. Wear rate of composites also decreases with increase in SiC content. SiC particles reduces the wear rate as well as coefficient of friction by providing the lubricating film on the counter surface which helps in reduction in wear rate of composites. Also, uniform dispersion of SiC particles helps in improving protection from corrosion. Maximum corrosion protection efficiency is found 56.58% at 20 wt.% of SiC.

Jamwal et al. [16] fabricated the Al/Al_2O_3-TiC composites using stir casting process and reported that wear rate of composites decreases with increase in reinforcement content. Also, tensile strength of composites is improved up to 149.3 MPa due to strong interfacial bonding of matrix material with Al_2O_3 and TiC. Vinod et al. [17] fabricated the A356 alloy RHA-Flyash reinforced hybrid metal matrix composites by double stir casting process and investigated the physical and mechanical properties of composites. It is found that mechanical properties of composites are improved due to addition of both organic and inorganic particles. Uniform dispersion of reinforcement particles helps to improve the mechanical properties of composites. Lower porosity is also found in composites due to reinforcement particles.

Present paper reports the primary processing techniques for manufacturing of Metal Matrix Composites. It also reports mechanical behaviour, commercialization and application of various techniques for the manufacture of Al_2O_3 reinforced aluminium matrix composites. This article is a comprehensive study of various processing techniques which have been adopted for the manufacture of metal matrix composites over the years. It is expected that aluminium based composites will be helpful in designing and developing components for light weight industries especially aerospace and aircrafts.

2. Primary processes for manufacturing of AMCs

Manufacturing route adopted in fabricating any composite plays a vital role in determining the final properties of the composite [18]. There are several techniques which are being adopted for the development of quality MMC products. Primary processes for manufacturing of AMCs at industrial scale can be classified into three main groups:

1) Solid state processes.
2) Liquid state processes.
3) Deposition processes.

2.1. *Solid state processes for manufacturing of AMCs*

2.1.1. *Powder blending and consolidation (P/M processing)*

The most widespread method in solid state processes is powder blending and consolidation process or powder metallurgy (P/M process). Its remarkable expansion is due to the fact that this technique was designed, developed and applied over traditional metallurgy and then adapted to the case of metal matrix composites [18]. Powder metallurgy processing technique is very attractive as it employs lower temperatures and thus, theoretically offers better control of interface kinetics. This processing method also makes it possible to employ matrix alloy compositions and microstructural refinements that are only available via the use of rapidly solidified powders. Processing of powder metallurgy composites has specific, required steps which is shown in Fig. 1.

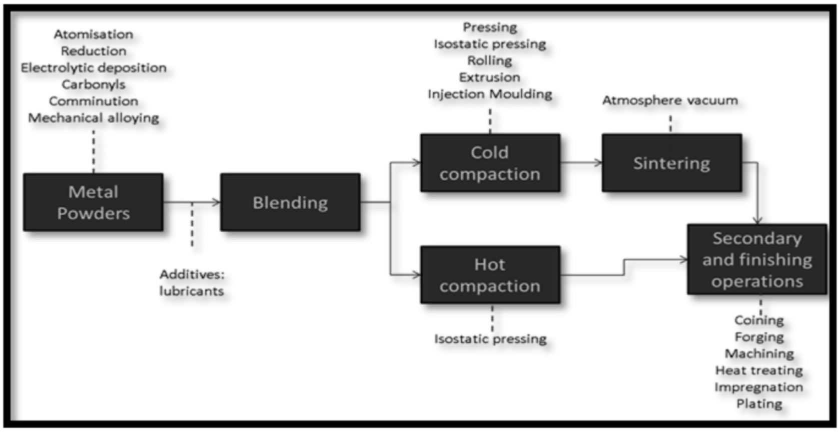


Fig. 1 – Powder metallurgy process.

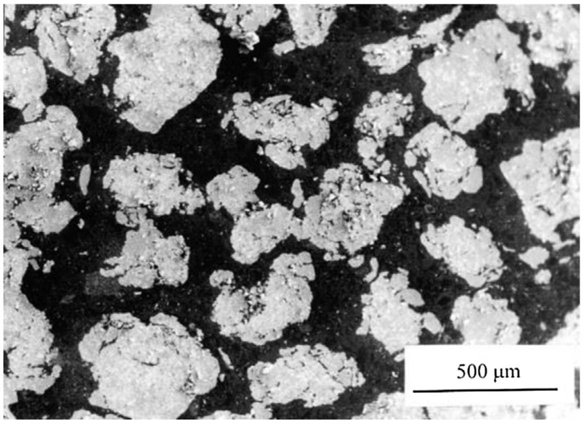


Fig. 2 – Microstructure of Al–$(AlO_3)_p$ composite powder [18].

1) First step regards weighing of the composition and preparation of the powder that will be constituents of the mixture to be processed in the successive stages i.e. powders of metal/metal alloy must be blended with the reinforcement.
2) Blended powders are then compacted into a 'green form', using uniaxial pressing or cold isostatic pressing. Green form or the green body thus obtained is approximately 80% dense.
3) In the third step sintering is done by heating the green body usually in an inert atmosphere to a desired processing temperature in order to obtain a sintered body [19]. The sintered body, typically, have a 100% theoretical density. There are basically three stages of sintering i.e. initial stage sintering, intermediate stage sintering and final stage sintering.

Al_2O_3 is a major reinforcement in aluminium matrix composites, which have been developed rapidly in recent years by powder metallurgy method. Aluminium powder and the reinforcement are blended and then compacted to form a green body. Green body is then sintered in a vacuum chamber to obtain sintered body having 100% theoretical density.

Microstructure of the composite powder is given in Fig. 2. A homogeneous particle distribution is observed in the micrograph as Al_2O_3 particles surround the matrix particles. It was seen using metallographic analysis that the coarser particles were more uniformly distributed, while finer particles tend to agglomerate, resulting in higher porosity [20]. Increase in the volume fraction of Al_2O_3 particle modifies the structure and leads to a homogeneous particle distribution.

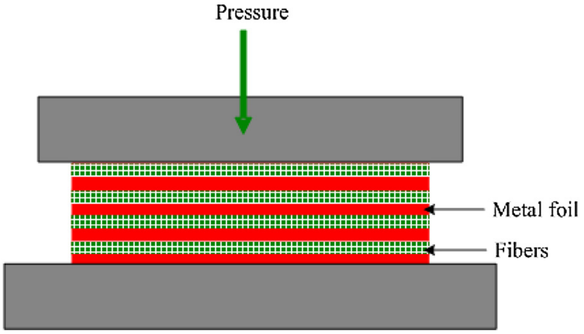


Fig. 3 – Diffusion bonding.

2.1.2. *Diffusion bonding*

Diffusion bonding processes were developed mainly for heat-sensitive materials; for materials with a tenacious oxide layer, and for composites that provide a high degree of difficulty for joining by other processes [21]. Technique of diffusion forming, particularly for the typical long composite fibre, consists of mechanical application of pressure and high temperature causing a process that would tightly bind matrix and fibre [22].

As shown in Fig. 3, diffusion bonding is a type of pressure welding technique which involves the inter-diffusion of atoms across the welding interface usually separated by solid or liquid state inter-layer. Hence, diffusion bonding requires the mating surfaces to be clean as the pieces to be joined together are brought within the atomic distance through localized plastic deformation in the weld zone. Diffusion bonding is a relatively simple joining process, controlled by three interrelated process parameters (a) the bonding temperature, (b) the bonding pressure and (c) holding or dwell time. The bonding temperature should be between 50 to 70% of the melting point (in absolute temperature) of either the lowest melting temperature or major phase. Bonding pressure should be high

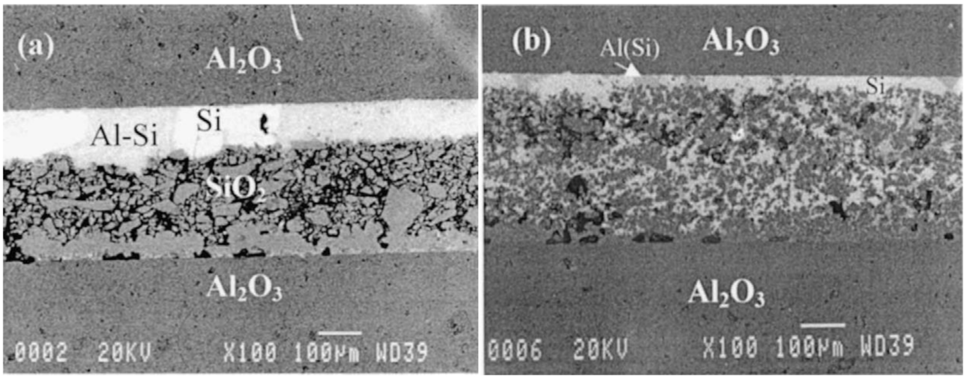


Fig. 4 – Scanning electron micrographs of cross-section of Al_2O_3/Al–Al_2O_3/Al_2O_3 joints fabricated from the penetration of Al into the porous SiO_2 layer at (a) 850 °C and (b) 1000 °C in a vacuum for 30 min at 100× [20].

enough to ensure a tight contact between the joining surfaces and sufficient to aid in the deformation of surface asperities to fill all the voids in the weld zone. Also, the holding time should be optimized for the diffusion process to take place, so as to achieve the desired joint quality and to form an intimate contact.

Alumina (Al_2O_3/Al_2O_3) joints and alumina/aluminium MMC (Al_2O_3/Al–MMC) joints were fabricated using an Al_2O_3–Al composite as an interlayer. The first step in Al_2O_3/Al_2O_3 joining process is the sintering of silicate glass on the surface of the Al_2O_3, followed by the reactive penetration of liquid aluminium into the sintered glass to form an interlayer of Al_2O_3–Al composite between the two Al_2O_3 pieces. To join Al_2O_3 to Al-MMC, after the fabrication of the Al_2O_3-Al composite layer on the surface of Al_2O_3 using the combination of sintering and reactive penetration, Al_2O_3/composite/MMC joints were fabricated by using diffusion bonding between the Al_2O_3–Al composite layer and the MMC. Scanning electron microscopy (SEM), XRD analysis and shear testing, respectively were used to examine the microstructures, phase composition and mechanical properties of the joints. Experimental analysis showed that the high porosity in the sintered glass led to the formation of a porous Al_2O_3–Al composite layer between two pieces of Al_2O_3. Fig. 4 shows the SEM micrographs of the cross-section of Al_2O_3/Al–Al_2O_3/Al_2O_3 joints fabricated from the penetration of Al into the porous silica layer at (a) 850 °C and (b) 1000 °C in a vacuum for 30 min respectively at 100X.

2.2. *Liquid state processes for manufacturing of AMCs*

2.2.1. *Stir casting*

In the stir casting process of composite manufacturing the reinforcement is introduced into molten metal by stirring. Stir casting process generally involves producing a melt of the selected matrix material, followed by the introduction of a reinforcing material into the melt and obtaining a suitable dispersion through stirring. Fig. 5 shows the stir casting of MgO reinforced aluminium (Al) matrix composite. Stir casting is one of the most economical techniques available to produce large near-net shape parts from MMCs which involves conventional stir mixing followed by casting [23]. Vortex technique is the simplest and most commercially used method among all stir casting routes. Vortex technique involves the introduction of pre-treated ceramic particles into the vortex of molten alloy created by the rotating impeller [24].

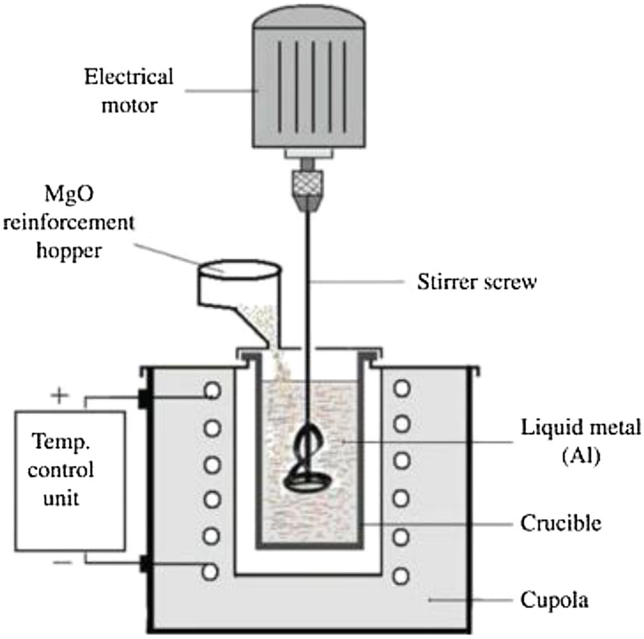


Fig. 5 – Stir Casting of MgO reinforced aluminium (Al) matrix composite.

First step in the vortex method is the incorporation of ceramic particles into the vortex formed by stirring of the molten metal. Next step is to stir the mixture after the particles are feed to the melt in order to obtain a uniform dispersion of the particles, and the final step is to cast the molten mixture to obtain the composite material. There are many manufacturing parameters like crucible size, ability and the size of impeller, temperature of the molten metal, stirring time, stirring speed, rate of particle feeding into the mixture, and temperature of the mould which need to be controlled to obtain a homogeneous mixture of reinforcement in the matrix. The two major challenges in this process are, firstly ceramic particles are generally not wetted by liquid metal matrix, and secondly,

Fig. 6 – SEM image of nano-Al_2O_3/Al composite powder at 100× [23].

reinforcing particles tend to sink or float depending on their density relative to the liquid metal and therefore dispersion of ceramic particles can be non-uniform [25].

In another study, pure aluminium ingot and particulate alumina powder were used as the matrix and reinforcement, respectively. Composite specimens were manufactured by stir casting method using mechanical mixing of the molten alloy. Examination of the composite microstructure showed that Al_2O_3 particles are uniformly distributed in the aluminium matrix, but in some regions clusters of smaller particles exist in the as-cast samples. Fig. 6 shows the SEM image of nano-Al_2O_3/Al composite powder at 100×.

2.2.2. *Infiltration process*

In the infiltration process a preform is made from reinforcing phase and then the melt is introduced into this preform to fill all the open porosity. In the systems where melt wets the reinforcement the flow may be brought about solely by the forces of capillarity; otherwise mechanical force need to be applied to overcome the resisting forces due to drag and capillary. Pressure required in combining the matrix and the reinforcement is a function of the friction effects due to the viscosity of molten matrix as it fills the ceramic preform. Wetting of the ceramic preform by the liquid alloy depends on different factors like alloy composition, ceramic preform material and surface morphology, temperature and time.

Fig. 7 shows infiltration of the preform by application of mechanical force using pressurized N_2 gas. In a study an Al metal matrix composite unidirectionally reinforced with continuous α-alumina fibres was fabricated by medium pressure infiltration technique using pure aluminium powder as the matrix material and continuous α-alumina fibres as the reinforcement material. Specimens were ground and polished. Optical micrographs were taken in a cross-section located in the middle of the sample. Fig. 8(a) and (b) is micrographs of Al_2O_3-Al composite processed by medium pressure infiltration at two in-plane sections taken at the middle of the sample [26]. These figures illustrate the fibres arrangement in the matrix. Hence, it appears that during infiltration of the composite some clustering of fibres occurs. This leads to some regions dispelled of fibres due to matrix flow. The clustering also creates some regions of higher fibre volume fraction.

2.2.3. *Spontaneous infiltration process*

Spontaneous Infiltration process is also known as pressure less infiltration process. In this process there is no use of external pressure or forces when the liquid metal enters into cavities. Controlled temperature and gaseous atmosphere are required for good wetting conditions. Many studies have been carried out in pressure-less infiltration process using Al-Si, Al–Mg and Al–Zn alloys into SiC preforms but still there are many challenges in Pressure-less infiltration process which limit its use in the industries. Poor wettability between reinforcement and matrix is the major drawback of pressure-less infiltration which results in the formation of oxide layer on the melted surface. Poor wettability influences the infiltration process by slowing down the fabrication process and undesirable reaction at the interfaces which result in the formation of intermetallic such as Al_3SiC_4 and Al_4C_3 in Al-SiC based composites. Some researchers have studied the effect of activator content in the spontaneous infiltration process of MMCs. Several studies reported that activator and dwell time controls the rate of infiltration in the pressure less infiltration process. It is also reported that wettability of preform by the molten metal is an important parameter for fabrication of composites by pressure less infiltration process. Wittig et al. [27] reported that

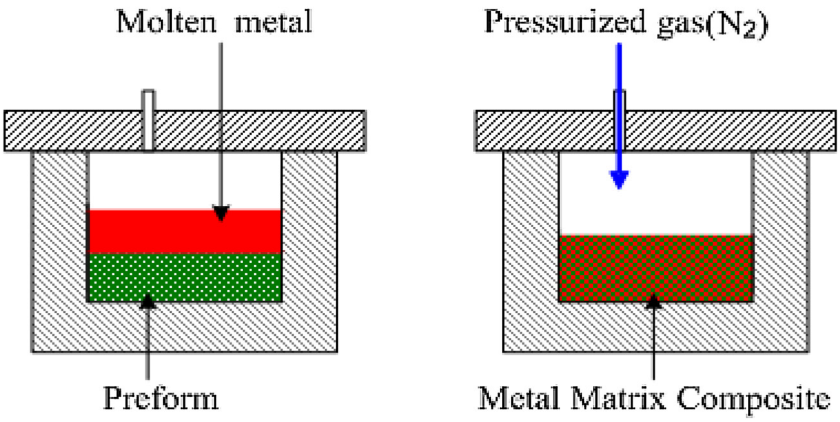
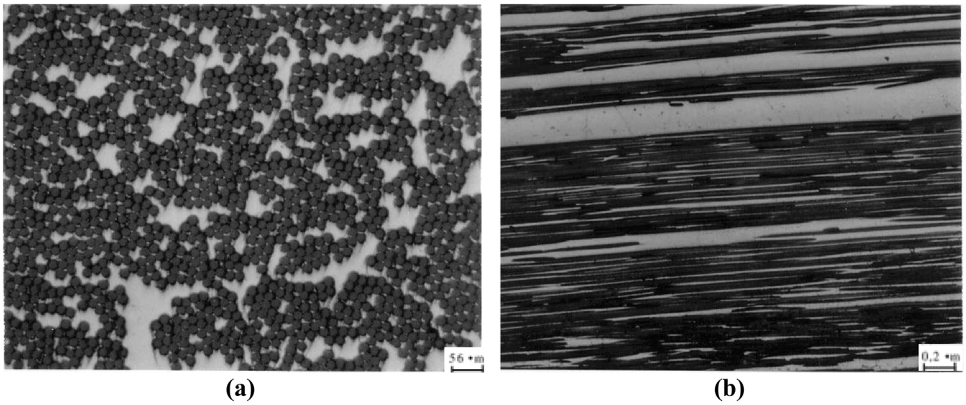


Fig. 7 – Infiltration of the preform by application of mechanical force using pressurized N_2 gas.



(a) (b)

Fig. 8 – Microstructure of Al_2O_3-Al composite processed by medium pressure infiltration at two in-plane sections [26].

wettability can be improved by using 100 Pct nitrogen atmosphere in furnace and addition of Mg into the melt because Mg is known as powerful surfactant that helps in accumulation of oxygen from the surface of melt and forms $MgAl_2O_4$ at the interface. This reaction acts as a driving force and helps to promote wetting.

2.2.4. *Forced infiltration*

In the forced infiltration process external pressure or mechanical force is used to govern the infiltration of molten metal into the porous reinforcement. It overcomes the drawback of poor adhesion between the reinforcement and matrix by the use of mechanical force which pushes the molten metal into the preform. Forced infiltration can be classified into different categories which are discussed in Fig. 9 and summarized below:

(a) Pressure die infiltration process.
(b) Gas pressure infiltration process.
(c) Squeeze casting infiltration process.
(d) Vaccum infiltration process.
(e) Lorentz force infiltration process.
(f) Ultrasonic infiltration process.
(g) Centrifugal infiltration process.

2.2.4.1. *Pressure die infiltration process:*. In this process the molten metal flows into the injection barrel. Then the molten material is forced into the mould from the barrel and is allowed to cool inside the mould. Once the material gets solidified in the mould then moulded part is ejected using the ejector pins. Feed sprue is also ejected from the cavities. Main advantage of the pressure die infiltration process is low cost and high precision along with complexity in fabrication. Pressure die infiltration process is shown in Fig. 10 below:

Pech-Canul et al. [28] investigated the effect of CNT reinforcement on the Mg alloy and reported that by adding only small amount of CNTs the mechanical properties of light weight composite materials is increased. It is also found that the compression failure of composite is increased up to 40% and ultimate compressive strength is increased upto 20% as compared to matrix material. Li et al. [29] fabricated the Al-4 mass% Cu alloy matrix composite by reinforcing both alumina fiber (Al_2O_{3f}) and alumina particle (Al_2O_{3p}) by low pressure infiltration process and investigated the wear resistance. It is found that with increase in Al_2O_{3f} vol.% to Al_2O_{3p} vol.% (f/p) there is reduction in infiltration defects. Hybrid MMC reinforced with 12.5 vol.% Al_2O_3 fiber with 7.5 vol% Al_2O_{3p} shows the maximum wear resistance because of 3-D distribution of fibers in hybrid-MMCs which protects Al_2O_{3p} from dropping-off. Demir et al. [30] reported that deformation of preform which occurs due to the pressure of molten metal during and before infiltration process is high in die casting as compared to squeeze casting.

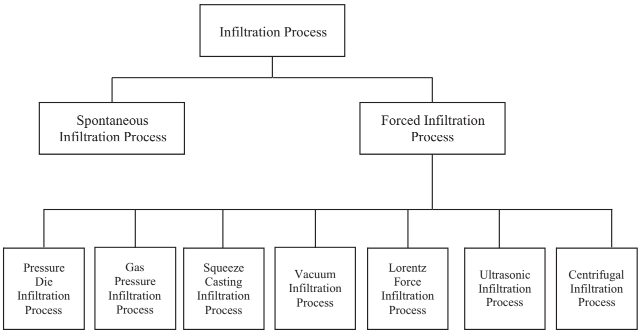


Fig. 9 – Infiltration process and its types.

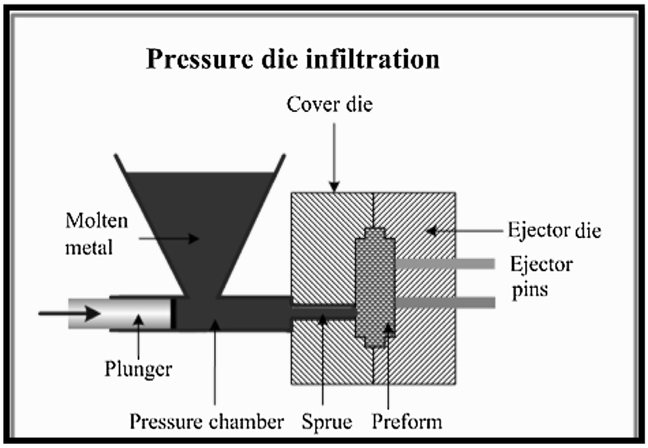


Fig. 10 – Pressure die infiltration process.

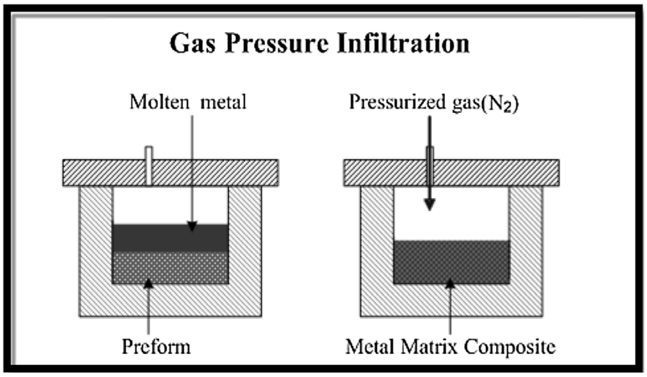


Fig. 11 – Gas Pressure Infiltration Process.

2.2.4.2. *Gas pressure infiltration process:*. Gas pressure infiltration process is an infiltration method in which liquid phase of matrix with the use of pressurized gas applies a specific amount of pressure on the molten matrix or the metal and forces it into the mould which is shown in Fig. 11. This process is generally carried out in the combination with vacuum at the other end of preform to avoid the entrapment of air which helps in easy penetration at the lower pressures. This method is used in large-scale production of the composite materials. There is very short contact time between the hot metal with the fibers. Gas pressure infiltration is the only method which results in low damage of fibers because of use of mechanical forces. Fukunaga et al. [31] reported that rate of infiltration is decreased by anti-pressure of gas in porous preform and it increases with increase in temperature and infiltration depth. High pressure is needed for infiltration of molten metal. Hence, anti-pressure of gases is considered during the analysis of threshold pressure. By using ideal gas equation PV = nRT, the anti-pressure of the gas is expressed by:

$$Pg\,(z) = \frac{PoTzL}{To[L - z\}} \tag{1}$$

where

P_o = pressure of gas at initial time
T_z = temperature of gas when infiltration attains height z.
L = total length of preform
T_o = initial time temperature

Qi et al. [32] reported that fabrication of MMCs by hydrostatic gas pressure infiltration have advantages like low fabrication cost and high operational flexibility for research purposes. The only drawback of gas infiltration technique is the higher cost of pressurized gas. Thermal conductivity of aluminium/diamond composites by gas pressure infiltration process was carried out and it was concluded that increase in contact time increases the thermal conductivity of the composites which is produced at relatively low temperatures such as 760 °C. Manu et al. [33] proposed a method of in-situ joining of Ti to Al/SiC composites by low pressure infiltration process.

2.2.4.3. *Squeeze casting infiltration process:*. Squeeze casting infiltration process is one of the widely used fabrication technique for the production of net shape MMCs with control over shapes, chemistry, volume fraction and distribution of reinforcement which is shown in Fig. 12. Squeeze casting infiltration process is also a forced infiltration process which allows the user to choose liquid phase fabrication of MMCs in which mould act as a movable part and applies the pressure on the molten matrix or metal. This helps in forcing the molten metal to penetrate into the dispersed phase, which is placed into the bottom fixed part of the mould. This process is almost similar to the squeeze casting process.

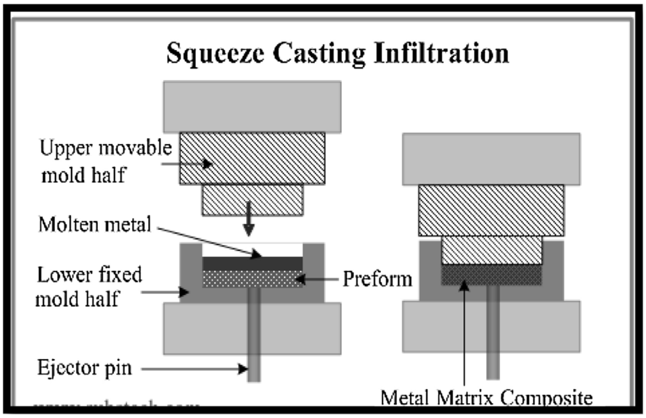


Fig. 12 – Squeeze casting infiltration process.

Li et al. [34] fabricated the carbon nanotube based light metal matrix composites with squeeze infiltration process by reinforcing it into Mg and Al alloys and concluded that composites reinforced with CNT shows lower density and high wear resistance. Xue et al. [35] reported that composite fabricated by squeeze casting infiltration process possess good dimensional accuracy with better surface finish, better creep strength, resistance to high temperatures, improved fatigue and higher corrosion resistance. Uozumi et al. [36] studied the effect of pressure and nickel coating on the microstructural development in continuous carbon-aluminium FRC fabricated by squeeze casting and concluded that pressure and nickel coating on carbon fibers improves the infiltration of molten metal into Carbon-fiber and hence less pressure is required for infiltration.

2.2.4.4. *Vacuum infiltration process:*. This process involves the negative pressure infiltration in which molten metal is penetrated into the evacuated preform because of application of suction pressure. In the vacuum infiltration the process parameters such as infiltration time, infiltration temperature, and applied vacuum plays an important role. It is found that with increase in the molten metal temperature infiltration rate also increases. Infiltration incubation period can be reduced by applying coating on the reinforcement which avoids the interfacial reaction. Main challenge in the vacuum infiltration process is the slow solidification rate of fabricated composite which enhances the grain growth and interfacial reactions between the reinforcement and matrix. During the fabrication process one portion of connection pipe is filled with steel chips which avoid the suction of molten metal getting into the pump. This is done to avoid the entrapment of molten metal into pipe and gets solidified in particular area with-out damaging the pump. Vijayaram et al. [37] investigated the effect of reinforcement volume fraction on dry sliding wear behaviour of Al-10Si/SiC_p composites fabricated by vacuum infiltration process. Sliding wear test was carried out under the loads (1224 and 36 N) at a sliding speed of 1.0 m/s using pin on disc wear and friction testing machine. It is found that reinforced composite shows better wear resistance as compared to unreinforced matrix. Wear rate increased with increase in applied load but it also decreases as there is increase in vol. fraction of SiC_p. Hajjari et al. [38] fabricated the Al-Ni coating based composite reinforced by SiC_p using vacuum infiltration process. It is found that infiltration rate is increased with increase in infiltration temperature and nickel coating thickness. Infiltration incubation time decreased with increase in nickel coating thickness. Gul et al. [39] fabricated the SiC_p reinforced Al-alloy composite by vacuum infiltration process using different volume fractions of ceramic particles. Mg was added to improve wettability between Al and reinforcement particles. It is found that with increase in infiltration time infiltration rate decreases. Density and hardness of the composites increase with increase in volume fraction of reinforcement. High wear rate is found at high loads but wear resistance increased with increase in volume fraction of reinforcement [40].

2.2.4.5. *Lorentz force infiltration process:*. This is a novel fabrication process in which molten metal is forced into the reinforcement by using electromagnetic force. In this process high frequency magnetic pulse is used to immerse the reinforcement into the molten metal. Lorentz force is produced by the interaction of eddy current with the magnetic pulse which helps to force the liquid metal to enter in reinforcement phase at a very high speed.

2.2.4.6. *Ultrasonic infiltration process:*. In Ultrasonic infiltration process ultrasonic vibrations generates the pressure waves which helps in the penetration of molten metal into the reinforcement phase. Acoustic cavitation is generated when ultrasonic vibration is actuated by a horn in the molten metal. When air is entrapped in the porous preform with dissolved gases in the molten metal it forms the cavitation nuclei. Infiltration process occurs due to collapse of bubbles which originates close to the molten metal. Ultrasonic power, fabrication speed and hole in the horn are the main important parameters for the ultrasonic infiltration process. It is found that with increase in the diameter of hole, the horn infiltration ratio decreases because of depletion in the formation of bubbles. Similarly, with increase in fabrication speed infiltration ratio decreases, but by adding Mg in the molten metal, increasing wettability helps in achieving better fabrication speed with increase in infiltration ratio.

2.2.4.7. *Centrifugal infiltration process:*. In this process rotational or centrifugal forces is used for the infiltration of preform with the molten metal. During the fabrication process, reinforcement is positioned inside a mould which have elongated runner and is filled with molten metal. There is requirement of large rotational velocities for infiltration process. Molten metal pressure is exerted on the reinforcement during the centrifugal force which is given by:

$$p_c = \frac{1}{2}p\omega^2(L_2^2 - L_1^2) \tag{2}$$

where,

p_c = pressure generated at the preform top surface during the rotation in centrifugal casting

p = density of the molten metal

ω = 2πΩ/60 where Ω is rotational speed (rpm)

L_2 = Outer molten metal level from the rotational axis

L_1 = Inner molten metal level from the rotational axis

In order to achieve high pressure centrifugal infiltration, L_1 is extended from the rotational axis, in such cases the pressure acting on the reinforcement phase is given by:

$$p_c = \frac{1}{2}p\omega^2 L_2^2 \tag{3}$$

2.2.5. *In-situ processing (reactive processing)*

Several different processes fall under this category including liquid–gas, liquid–solid, liquid–liquid and mixed salt reactions. In this process, in-situ chemical reaction between elements or between elements and compounds during composite fabrication process leads to the formation of the reinforcement phases in metallic matrix [41]. A good understanding of thermodynamics and reaction kinetics is required in order to obtain the desirable end product using in-situ process. Composites synthesized using in-situ techniques exhibit the presence of a uniform distribution of reinforcement that tends to be fine and is associated with a clean interface with the metallic matrix, which assists in the formation of a stronger bond between the reinforcement and the metallic matrix [42]. Direct melt reaction (DMR) process, reactive hot pressing (RHP), and self-propagating high temperature synthesis (SHS) are some of the in-situ processing techniques developed to fabricate MMCs. Due to its simplicity, low cost and near net-shape forming capability, the DMR process is considered as one of the most promising in-situ processing techniques for commercial applications [43].

MMCs fabricated by in-situ process have several advantages like, the in-situ formed reinforcement phases are thermodynamically stable, free from surface contamination, have finer sizes and disperse more uniformly in the matrix, leading to stronger particle-matrix bonding.

In-situ DMR is used to fabricate Al_2O_{3p}/Al composites from Al-CeO_2 system. Studies show that the in-situ chemical reaction between Al melt and CeO_2 powder can proceed spontaneously when the temperature is held at 800–900 °C. Due to the DMR, the in-situ generated Al_2O_3 particles are in nanoscale, with size in the 100–200 nm range. Moreover, the composites have high isotropic properties due to uniform dispersion of Al_2O_3 particles in matrix along with high density of dislocations. The interface between particle and matrix is clean as there is no impurity at the interfaces between reinforcements and aluminium matrix [44]. Fig. 13 shows the in-situ processing by controlled unidirectional solidification of a eutectic alloy. Fig. 14 shows the distribution and morphology of particles in the composite through SEM analysis of particles in the in-situ Al_2O_{3p}/Al composite distribution and

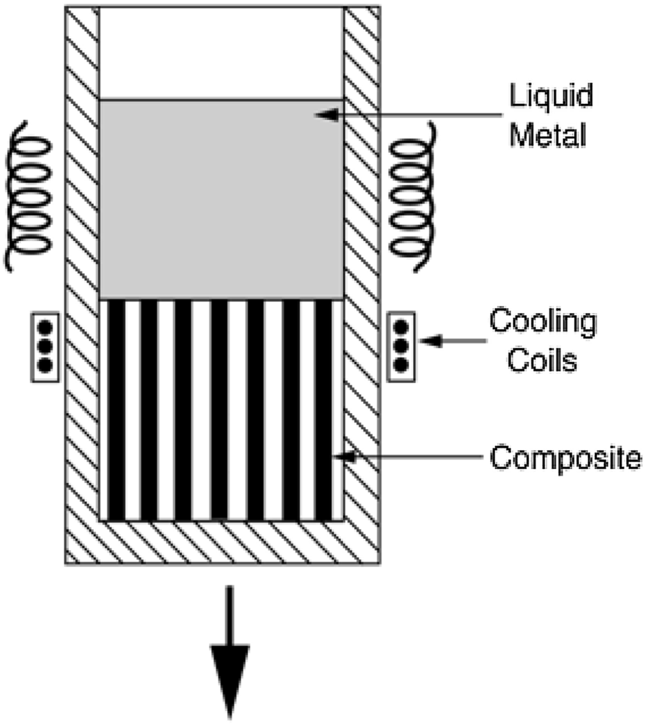


Fig. 13 – In situ processing by controlled unidirectional solidification of a eutectic alloy [42].

morphology of particles in composites (500× and insat image at 10,000×).

2.3. Deposition process

2.3.1. Physical vapour deposition (PVD)

Physical vapour deposition process is used for the manufacture of metal matrix composites and is generally a very slow process. In this process fibre is continuously passed through a region of high partial pressure of the metal to be deposited, where condensation takes place so as to get a relatively thick coating on the fibre [45, 46]. A high-power electron beam is directed onto the end of a solid bar feed stock to produce vapours. Deposition rates are 5–10 μm per minute typically. The coated fibres are assembled into a bundle or array and consolidated in a hot press or HIP operation to get the final composite material.

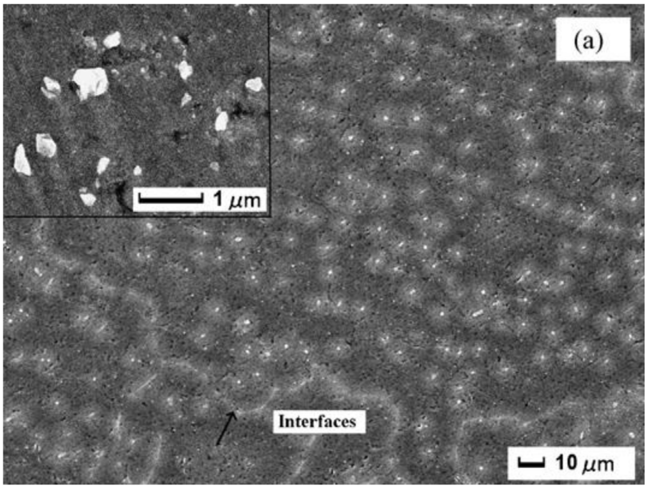


Fig. 14 – SEM analysis of particles for the in-situ Al_2O_{3p}/Al composites (a) distribution and morphology of particles in composites (500× and insat image at 10,000×) [43].

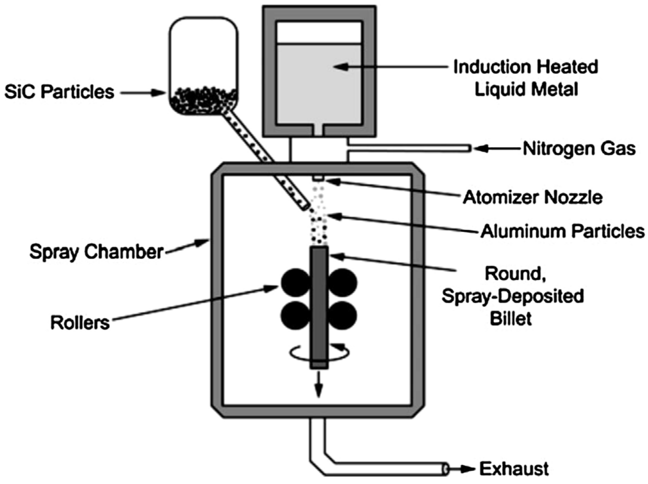


Fig. 15 – The spray deposition process [47].

PVD can be divided into two main categories:

1 Vaporization and characterization techniques (EBED).
2 Sputtering techniques.

In the EBED method a gun produces a high energy electron beam (EB), which vaporizes the matrix material and produces the metal vapour to condense on the fibre. Whereas in sputtering technique a piece of coating is bombarded with ions of the processing gas (such as argon), which breaks off atoms from the work piece thus sketching on the fibre.

2.3.2. Spray deposition

Spray deposition techniques fall into two distinct classes, depending on whether the droplet stream is produced from a molten bath (osprey process) or by continuous feeding of cold metal into a zone of rapid heat injection (thermal spray process) [47]. Fig. 15 shows the spray deposition process.

Spray forming technique, also known as Osprey process is an efficient method to produce near-net shaped components. This process take place in two steps, first step involves atomizing liquid melt into fine droplets using inert gas as an atomizing agent and subsequent deposition of fine droplets on a metallic substrate occurs in the second step. Deposition rate, flight length (i.e., nozzle to substrate distance), angle of spraying, atomizing pressure, atomizing gas etc. are some of the important processing parameters for the spray forming process [48].

Thermal spray is a plasma spray method, used extensively for depositing metallic and ceramic coatings for different purpose [49,50]. Plasma spray forming (PSF) is the modified technique for the architecture of wide range of alloys, inter-metallics, ceramics, composites and functional gradient

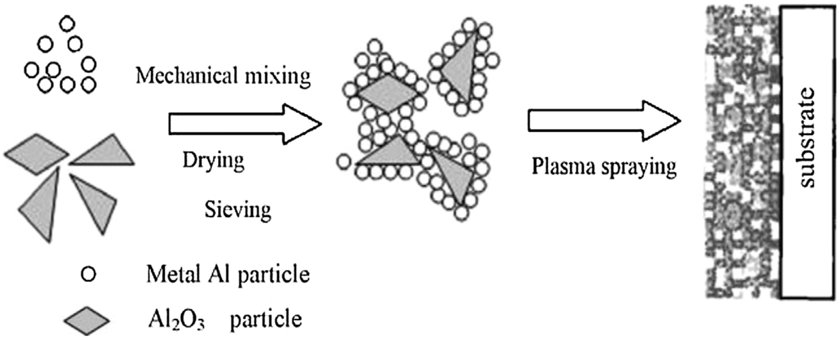


Fig. 16 – The schematic diagram showing concept of spraying powder design of Al_2O_3–Al composite [52].

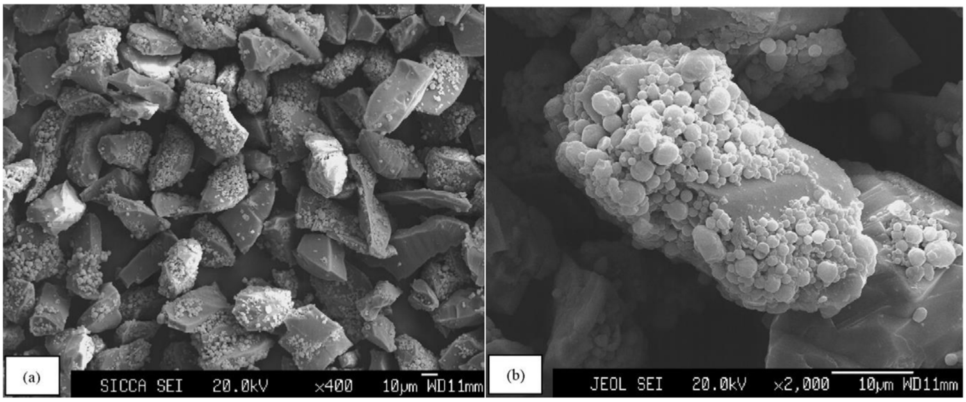


Fig. 17 – SEM micrographs of Al_2O_3–Al composite powders fabricated by plasma spraying at 400× and 2000× [52].

materials [51,52]. In this method molten particles are directed towards a rotating mandrel where they deposit, rapidly cool and form the desired shape. Plasma gun and the mandrel are controlled by computer and thus allow fabrication of complex shapes. This process results in the fabrication of parts sprayed to the near-net shape.

For example, Al_2O_3 and Al_2O_3–Al composite coatings were deposited by plasma spraying. Al additive effects and the correlation between coating microstructure, mechanical properties and wear resistance were investigated. X-ray diffraction (XRD) was used to determine phase composition of powders and as-sprayed coatings, while optical microscopy (OM) and scanning electron microscopy (SEM) were employed to investigate the morphology of impacted droplets, polished and fractured surface. Fig. 16 shows the schematic diagram illustrating concept of spraying powder design of Al_2O_3–Al composite. The Al_2O_3–Al coating exhibited homogeneously dispersed pores and the co-sprayed Al particles were considered to be distributed in the splat boundary. Fig. 17 shows the SEM micrographs of Al_2O_3–Al composite powders fabricated by plasma spraying at 400X and 2000X.

3. Effect of processing parameters on mechanical behavior of aluminium matrix composites

Metal matrix composites (MMCs) possess high modulus, fracture and compressive strength. They also show improved thermal, wear and corrosion resistance. The characteristics of powder metallurgy processed metal matrix composites are greatly influenced by:

1. Percentage of the reinforcement.
2. Structural characteristics which depend on the processing parameters and heat treatment schedule.
3. Bonding between the dispersoids and the matrix.

Rahimian et al. synthesized Al-Al_2O_3 composites via powder metallurgy technique to study the effect of particle size of alumina, sintering temperature and sintering time on different properties of the composite material [53]. Average particle size of alumina used was 3, 12 and 48 µm (Fig. 18) respectively, sintering temperature was increased from 500 to 600 °C and sintering time varied from 30 to 90 min. Figs. 19 and 20 show the effect of sintering time (45, 60 and 90 min at 600 °C) and sintering temperature (500, 550 and 600 °C for 45 min) respectively on the microstructure of the composite. The amount of densification increased as the sintering time was increased from 45 to 90 min. Also, it was seen that at higher sintering temperatures there is a formation of a denser structure due to higher diffusion rates. Manifestation of the evolution of microstructure with sintering temperature can be clearly seen by the changes in the morphology and the size of the grains and pores respectively. The investigated properties include density, hardness, microstructure, yield strength, compressive strength and elongation at fracture. A correlation was established between the microstructure and mechanical properties

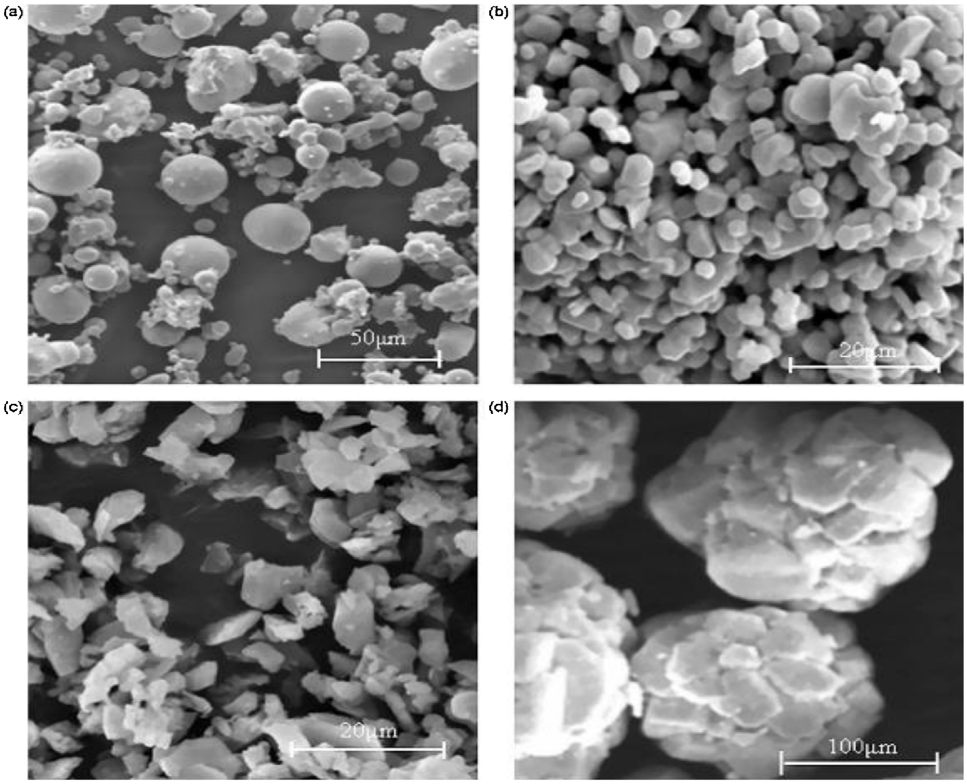


Fig. 18 – SEM micrographs of Al and Al_2O_3 powders (a) Al (b) Al_2O_3-3 μm (c) Al_2O_3-12 μm and (d) Al_2O_3-48 μm [53].

from which it was concluded that with decrease in the alumina particle size, the density of composite first increased upto a point and then decreased. In addition, for low particle size, hardness, yield strength, compressive strength and elongation at fracture were higher as compared to coarse particles. The properties of Al-Al_2O_3 composite are also dependent on both the sintering temperature and time. Prolonged sintering times had an adverse effect on the strength of the composite material.

Rabiei et al. [54] experimentally evaluated the fracture toughness of the aluminum matrix composites with various particle reinforcements. The results were compared with the fracture toughness using the Hahn–Rosenfield model. It was observed that the validity range of the Hahn–Rosenfield model was for reinforcement particles of size between 5–10 μm. The model was modified to estimate the fracture toughness of the metal matrix composites with larger particle reinforcements and the modified model was tested experimentally. A close agreement was found between the experimental results and the predicted toughness using the modified fracture model.

For the stir casting process, it has been showed that nano-Al_2O_3 particles are dispersed homogeneously throughout the matrix. An increase in porosity was observed by adding nano-particles, due to increase in the contact surface between molten aluminium and nano-particles. Porosity levels also increased with increase in stirring time due to improved agitation in molten composite. Hardness and tensile properties also improved upon addition of nano-Al_2O_3 particles. The changes in mechanical properties of the composites were found to be consistent with the variations in porosity content of the composites. It was also observed that wettability of particles within the molten matrix decreased by increasing the reinforcement percentage and decreasing the reinforcement size.

4. Commercialization of aluminum matrix composites

Economic aspects of any materials have the greatest concern in their large-scale commercialization. Global markets for aluminum based composite technologies and products are in manufacturing, structural materials, and others industrial sectors. According to markets and market analysis, the global aluminum-based composites market is expected to reach record high in near future. The commercial scale production of aluminum-based composites aimed at industrial applications has grown significantly in the last few years, especially since many companies from China have entered the market. Compared with large-scale production of aluminum based composites, use of other metallic composites are very low. Almost all the manufacturer has started using aluminum-based composites materials in production for very small units to giant merchandises. China is one of the biggest aluminum based composites manufacturing country in the world. Number of issues need to be addressed to advance the commercial applications of aluminum-based composites. Similar to other, the cost/performance ratio of aluminum-based composites is the greatest concern for industries during determination whether aluminum-based composites can be used in their products. The cost of aluminum-based composites is not a

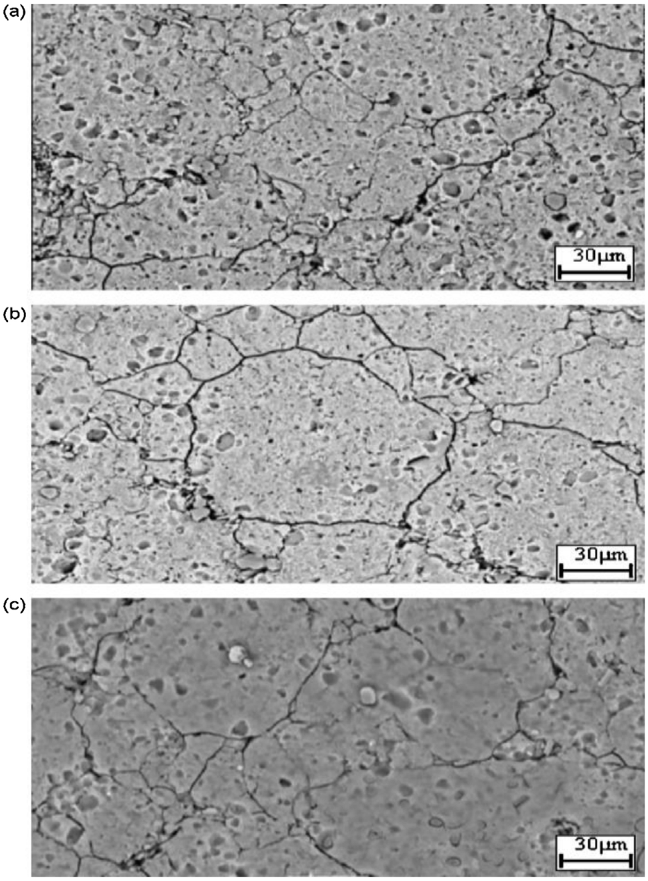


Fig. 19 – Effect of sintering time on microstructure of composites at 600 °C (a) 45 (b) 60 and (c) 90 min [53].

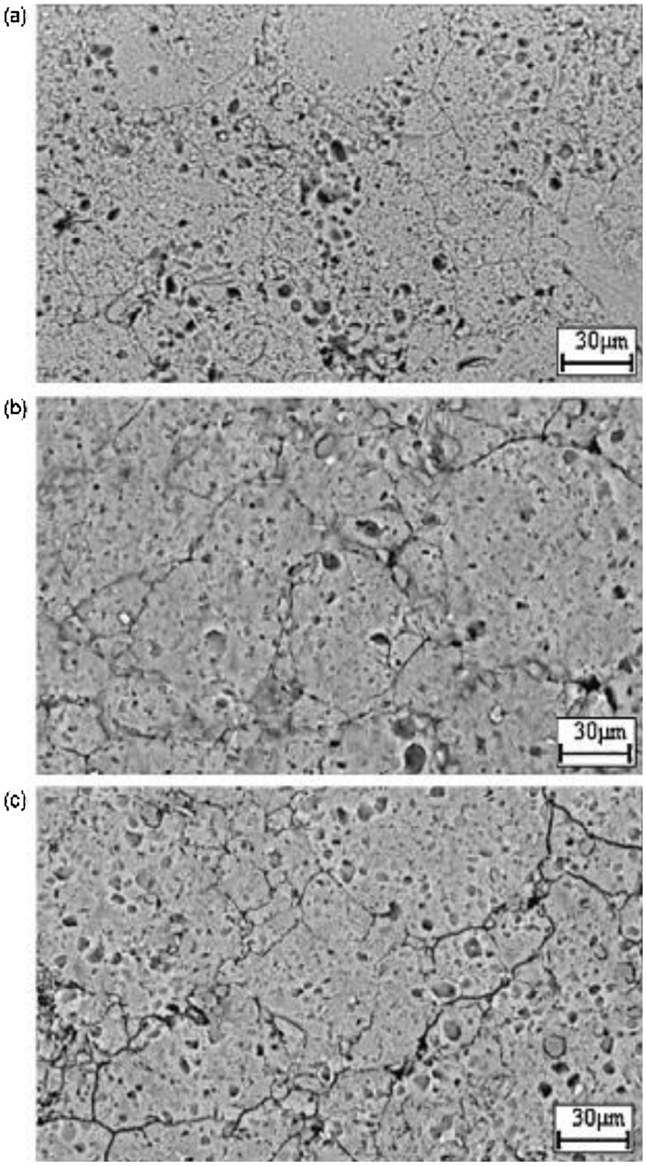


Fig. 20 – Effect of sintering temperature on microstructure of composites after sintering for 45 min (a) 500, (b) 550 and (c) 600 °C [53].

big challenge to compete with other existing materials, however, when aluminum-based composites will get its optimum application in industries, and when will manufacturers start to make a profit from material is still a big question. Overall, it is expected that very soon large-scale commercial utilization of aluminum-based composites is going to happen [55-58].

5. Industrial applications of aluminum matrix composites

Aluminum matrix composite has many applications in engineering at present time. The development in aluminum matrix composites forced many industries to adopt aluminum-based composites over aluminum alloys and pure aluminum due to its superior properties than its alloys. Some of industrial applications of aluminum matrix composites are discussed below:

1 Automobile Sector: Components such as pistons, connecting rods, engine blocks, brake rotors, current collectors, propeller shafts and brake disc.
2 Aerospace and aircraft industry: Wings and supporting structure in airlines, fuselage, military aircrafts and cargo.
3 Rail transport: Use of aluminium in the designing of railway cars provides better fuel efficiency and higher load carrying capacities. Durability of aluminum matrix composites makes them suitable choice in material selection for rail transport.
4 Marine transport: Use of aluminum-based composites in marine engineering provides high speeds to boats at higher fuel efficiency as well as it reduces the maintenance costs as compared to other materials.
5 Off-shore applications: Aluminium matrix composites are widely used in offshore platforms and seawalls. AMCs provide greater strength in supporting structure at lower costs as compared to other materials.
6 Building and construction materials: Strength and stiffness are the major requirements for building materials. AMCs provide greater strength and stiffness to supporting structure in building materials which makes them suitable choice in material selection for building materials.

7 Packaging and Containerization Sector: It is used in beverage bottles and cans, industrial foils and food containers.
8 Sports and recreation: The development of sports goods with a reinforcement of boron and silicon carbide in Aluminium provides greater strength in light weight.
9 Electrical transmission: Properties of AMCs such as higher corrosion resistance, high efficiency in electrical conduction and light in weight makes them suitable materials in electrical transmission applications.

6. Concluding remarks

Each of the processes discussed above have their own advantages and limitations. The choice of the fabrication techniques is influenced by many factors like production cost, process efficiency, the quality desired in the product and their applications etc. Powder metallurgy processing technique is attractive for several reasons as it offers better control of interface kinetics since it employs lower processing temperatures. Powder metallurgy method also makes it possible to employ matrix alloy compositions and microstructural refinements that are only available through the use of rapidly solidified powders.

Diffusion bonding process is relatively easy to apply, highly productive, applicable to diverse situations and the resultant joint material has uniform properties. Consequently, the demands of the composite materials processed using the modern diffusion bonding techniques have increased greatly. But, the difficulties and high cost of removing the oxide layer and the maintenance of a clean surface have limited the application of diffusion-bonding process in many industrial applications. The diffusion bonding process is cumbersome for obtaining high fibre volume fraction and for homogeneous fibre distribution. The process is not suitable for producing complex shapes and components.

Conventional stir mixing followed by casting is one of the most economical techniques available to produce large near-net shaped parts from MMCs. This method cannot be easily used to synthesize nanocomposites as nano-sized ceramic particle reinforced aluminium matrix composites fabricated using conventional stir casting technique usually have poor distribution of nanoparticles within the matrix and also show high porosity. Fabrication of Al-matrix composites with alumina particles by casting process is usually difficult due to very low wettability of alumina particles along with agglomeration phenomena which results in non-uniform distribution and weak mechanical properties. It is costly and difficult to manufacture the metal matrix composites because of the poor wetting between matrix alloys and some reinforcements.

Some level of porosity and local variations in the volume fraction of the reinforcement are often noticed in the MMCs processed by infiltration technique. This process is seen to be a highly versatile, near net shape fabrication technique which offers very good control of the microstructure. Disadvantages mainly involved the high tooling costs and the fact that reinforcement must be mechanically self-supported prior to infiltration. This latter point limits the type of reinforcement geometries which may be employed.

The in-situ formed reinforcement phases are thermodynamically stable, free of surface contamination and disperse more uniformly in matrix, leading to stronger particle–matrix bonding. At the same time, the in-situ formed reinforcement phases have finer sizes. The composites synthesized using in-situ techniques exhibit the presence of a uniform distribution of reinforcement that ends to be fine and associated with a clean interface with the metallic matrix, which assists in the formation of a stronger bond between the reinforcement and the metallic matrix.

Deposition process has the main advantage that the matrix microstructure exhibits very fine grain sizes and low segregation, but has several drawbacks: the technique can only be used with discontinuous reinforcements, the costs are high, and the products are limited to the simple shapes that are obtained by extrusion, rolling or forging. Composites with uniform distribution of fibre and volume fraction as high as 80% can be produced by physical vapour deposition technique. MMCs processed by spray deposition technique are relatively inexpensive with cost that is usually intermediate between stir casting and P/M processes. Spray deposition technique is particularly useful for synthesis of materials (alloys/metal matrix composite), which are difficult to prepare by conventional processes.

Conflicts of interest

The authors declare no conflicts of interest.

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