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Review on Nano Particle Reinforced Aluminum Metal Matrix Composites

Endalkachew Mosisa, V. Yu Bazhin and Sergey Savchenkov
National Mineral Resources University, Saint Petersburg, Russia

Abstract: The need for lightweight, high strength materials has been recognized since the invention of the airplane. The inadequacy of lightweight metals and alloys in providing high strength to weight ratio led to the development of Metal Matrix Composites (MMCs). The introduction of a ceramic material into the matrix produces a composite material that results in an attractive combination of physical and mechanical properties which cannot be obtained with monolithic alloys. Nowadays different types of metals matrix predominately Al, Mg and Cu have been employed for the production of composite reinforced by nano sized ceramic particle such as carbides, nitrides and oxides. Wide range of property combinations also can be obtained by appropriate selection of metal matrix material, processing methods and the reinforcement phase. Comparatively among all MMCs, aluminium based particle reinforced MMCs have a large potential for a number of engineering applications, due to the fact that nano sized particle reinforced Aluminium Metal Matrix Composite (AMMCs) possess superior high strength to weight ratio, high hardness, fatigue strength and wear resistance. Hence, strengthening mechanisms and property improvement of aluminium based metal matrix composite have attracted the attention of researchers. This work aims to review the most popular processing methods, strengthening mechanisms and wettability of nano particle reinforced aluminium MMCs.

Key words: Metal matrix, reinforcement particle, metal matrix composites, strengthening mechanism, methods

INTRODUCTION

In a metal matrix composite, three important features determine its characteristics: viz. the matrix, the reinforcement and the matrix-reinforcement interface. Matrix is the continuous phase and its properties are improved by converting it into a composite with the introduction of an appropriate reinforcement. The reinforcement is hard secondary phase incorporated may be in the form of whiskers, particles or rods in to the alloy matrices to produce metal matrix composite which has better mechanical properties (Sanaty-Zadeh, 2012; Ham, 1969). Metal matrix composite is refers to a composite consist of metal or alloy, combined with metal or non-metallic reinforcement. The addition of high modulus and high strength refractory particle produces composite whose properties are in between matrix and reinforcement. These properties are not achievable with lightweight monolithic aluminium, magnesium and titanium alloys.

There are various materials used as reinforcement for nano composite such as Al_2O_3, SiC, TiC, B_4C, etc. The most commonly used reinforcements are Silicon Carbide (SiC), Boron Carbide (B_4C) and Aluminium Oxide (Al_2O_3). The volume, shape of the reinforcement, location of the reinforcement and fabrication method can be varied to achieve the required properties metal matrix composite. In addition, the distribution of reinforcement particles and the interfacial, reaction between the matrix and reinforcement highly depends on the processing methods (Ham, 1969).

The selection of reinforcement or the matrix alloys largely depends upon the end use and the amenability for production (Ellis, 1996). Presently, from all metal matrix composites, AMMCs reinforced with ceramic particles has gained extensive applications in automotive and aerospace industries due to their better mechanical properties (Skoglund *et al*., 2002).

There are many processes viable to fabricate AMMCs and the objectives of the processing techniques are to homogeneously distribute the reinforcement phases to achieve defect free microstructure as well as economical efficient. The most common manufacturing MMCs technologies are divided into two main groups: primary and the secondary processing. Primary processing types of AMMCs also broadly categorized into: liquid state processing techniques and solid state processing techniques. In the liquid state processing methods, wettability of the reinforcement particles with matrix plays vital role and improved by using some alloying elements as wetting agents (Murty *et al*., 2003). This research is reviewed the processing methods, strengthening mechanisms and wettability of nano particle reinforced AMMCs.

Corresponding Author: Endalkachew Mosisa, National Mineral Resources University, Saint Petersburg, Russia

ALUMINIUM ALLOYS

Pure aluminum melts at 660°C; this relatively low melting temperature in comparison to most of other potential matrix metals which facilitates processing of Al based MMCs by primary and the secondary processing methods. Al-alloys are broadly classified as either wrought or cast materials (Chawla and Shen, 2001). The designation schemes for both wrought and cast alloys are based on the major alloying additions. Both wrought and cast alloy compositions may be further classified according to the method of obtaining mechanical properties: heat treatable or non-heat treatable (Hashim *et al*., 2001).

Heat treatable refers to alloys that can be strengthened by thermal treatment. Wrought alloys of the 2XXX, 6XXX and 7XXX series are generally heat treatable and those that contain major additions of lithium like 8XXX alloys are also heat treatable. Wrought alloys of the 1XXX, 3XXX, 4XXX and 5XXX series are non-heat treatable which means that they are not appreciably strengthened by heat treatment. Wrought alloys are designated by four digits while cast compositions are designated by three digits. Table 1 shows designation of aluminium alloys according to Aluminum Association (AA) and American National Standards Institute (ANSI).

Table 1: Designation for aluminum alloys

	Designation	
Major alloying element(s)	Wrought	Cast
None	1XXX	1XX
Cu	2XXX	2XX
Mn	3XXX	-
Si + Mg; Si +Cu; Si + Mg +Cu		3XX
Si	4XXX	4XX
Mg	5XXX	5XX
Mg + Si	6XXX	-
Zn	7XXX	7XX
Other than above	8XXX	-
Sn		8XX

REINFORCEMENT PARTICLE FOR ALUMINUM ALLOYS

The reinforcement phase in the metal matrix composite is the secondary phase. Large particle and dispersion strengthened composites are the two sub-classifications of particle reinforced composites. The distinction between large particle composite and dispersion-strengthened composites are based upon their reinforcement or strengthening mechanism (Dieter, 1988).

Large particle composite: Large particle composite is a type of particle reinforced composite where in particle-matrix interactions cannot be treated on an atomic or molecular level. Properties are a combination of those of the components. The rule mixture equations (Eq. 1 and 2) are two mathematical expressions have been formulated for the dependence of the elastic modulus on the volume fraction of the constituent phases for a two phase composite (Dieter, 1988).

The rule of mixtures: Rule of mixtures equations predict that the elastic modulus of the composite should fall between an upper bound and a lower limit by Eq. 1 and 2:

$$E_c(u) = V_m E_m + V_p E_p \quad (1)$$

A lower limit is given by:

$$E_c(l) = \frac{E_m E_p}{V_m E_m + V_p E_m} \quad (2)$$

Where:
E_c = Elastic modulus of composite
E_p = Elastic modulus of particle
E_m = Elastic modulus of matrix
V_m = Volume fraction of matrix
V_p = Volume fraction of particle

Concrete is a common example of large-particle composite.

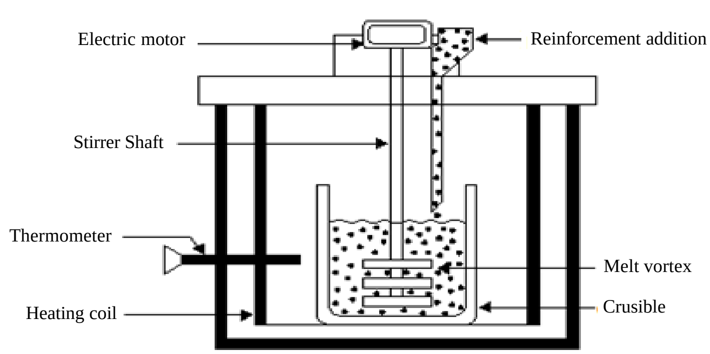

Fig. 1: Stir casting process

Dispersion-strengthened composites: This type of composite contains small particulates usually less than 0.1 µm or dispersions which increase the strength of (Fig. 1) the composite by blocking the movement of dislocations (Dieter, 1988). Disc brake system trains and automobiles, flight control hydraulic, Fan Exit Guide Vane (FEGV) are some of engineering products manufactured nowadays from nano ceramic particle reinforced aluminium alloys.

MANUFACTURING PROCESSES OF MMCS

There are many processes viable to fabricate AMMCs and the objectives of the processing techniques are to homogeneously distribute the reinforcement phases to achieve a defect free micro-structure as well as economical efficient. Primary industrial manufacturing processes of AMMCs can be classified into liquid phase and solid state processes (Dieter, 1988). Liquid phase processing is characterized by intimate interfacial contact and hence strong bonding but can lead to the formation of a brittle interfacial layer. Solid state processes include powder blending followed by consolidation, diffusion bonding and vapor deposition. Liquid phase processes include squeeze casting and squeeze infiltration, spray deposition, slurry casting (compo-casting) and reactive processing (insitu composites).

Choosing the appropriate manufacturing process is an important consideration at the early stages of metal matric composite design. The selection of the processing route depends on many factors including type and level of reinforcement loading and the degree of micro structural integrity desired (Murty *et al*., 2003). In this work some popular primary manufacturing processes of aluminium MMCs are briefly reviewed.

Liquid phase manufacturing processes: Most of the MMCs are produced by this technique. In this technique, the ceramic particles are incorporated into liquid metal using various processes. The liquid composite slurry is subsequently cast into various shapes by conventional casting techniques or cast into ingots for secondary processing. The process has major advantage that the production costs of MMCs are very low. The major difficulty in such processes is the non-wettability of the particles by liquid aluminium and the consequent rejection of the particles from the melt, non-uniform distribution of particles due to their preferential segregation and extensive interfacial reaction.

Stir casting process: Stir casting is a primary process of composite production. Selected type, size and volume fraction of reinforcement material incorporated into the molten metal or matrix and stirred thoroughly for a homogeneous distribution with in the matrix alloys. The resultant molten alloy with ceramic particles can then be used for die casting, permanent mold casting or sand casting as shown in Fig. 2. Among discontinuous metal matrix composites, stir casting is generally accepted as a particularly promising route and currently practiced commercially. Its advantages lie in its simplicity, flexibility, better matrix reinforcement bonding and applicability to large quantity production (Zhang *et al*., 2006). Most of the time, major problems associated with stir casting of aluminum MMCs are heterogeneous distribution of the reinforcement material and poor wettability.

The following factors needs considerable attention in stir casting process for mechanical properties improvement of aluminium based MMCs (Lloyd *et al*., 1989):

- The type, size and weight fraction of the reinforcing particles

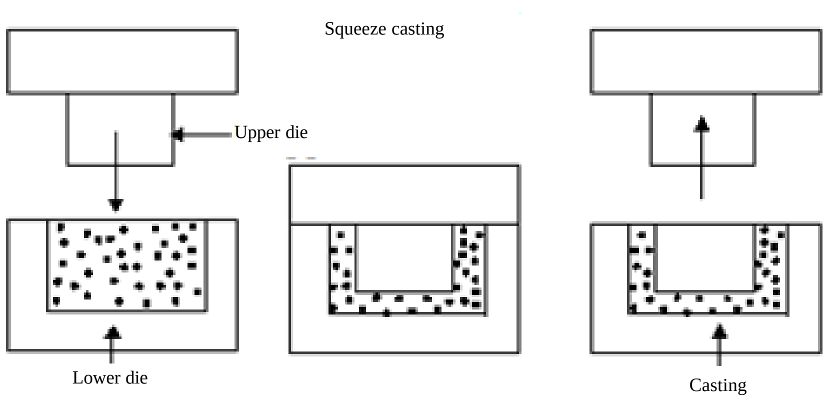

Fig. 2: Squeeze casting

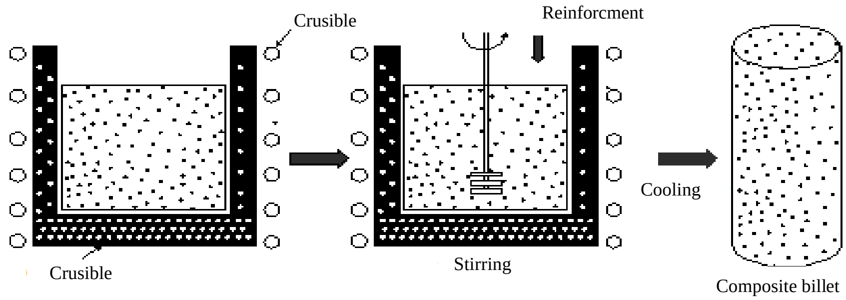

Fig. 3: Compo-casting process

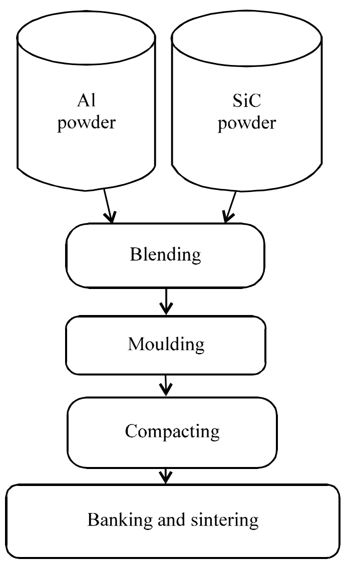

Fig. 4: Powder metallurgy processes

- Stirring rate, Stirring time, stirring temperature and pouring temperature
- Wettability between the matrix and reinforcement material
- Porosity in the cast metal matrix composites
- Chemical reactions between the reinforcement and the matrix alloy

Squeeze casting process: Squeeze casting is liquid phase processing technique in which particle reinforced MMCs solidifies under high pressure (50-100 MPa) to produce close tolerance of MMCs within closed dies positioned between the plates of a hydraulic press.The applied pressure and instant contact of the molten metal with the die surface produce a rapid heat transfer condition that yields a pore free fine grain casting with mechanical properties approaching those of a wrought product. Squeeze casting process is easily automated as shown in Fig. 3 to produce near net to net shape high-quality components.

The process is basically divided into two types: direct and indirect squeeze casting. Direct process is when the squeeze pressure applied to MMCs through the die-closing punch itself, whereas in the indirect process, the squeeze pressure is applied after closing of die by a secondary ram. Major advantages of squeeze casting (Sanaty-Zadeh, 2012):

- The parts produced are without gas porosity or shrinkage porosity
- Feeders or risers are not required and reduces metal wastage
- Fluidity is not critical, can be squeeze cast to finished shape with the help of pressure and
- Squeeze castings can have mechanical properties as good as wrought products

Compo-casting: Compo-casting process is the improved process of slush-or stir-casting in which the reinforcement particles are added to a metallic alloy matrix at a temperature with the semi solid state range (Kainer, 2006). A schematic of the compo-casting steps followed to manufacture composites is shown in Fig. 4. Liquid metal is stirred as solid reinforcement particles are added to the melt to produce slurry. Stirring continues as the melt is cooled until the metal itself becomes semi-solid and traps the reinforcement particles in a uniform dispersion. Further cooling and solidification then takes place without additional stirring. The slurry transferred directly to a shaped mold prior to complete solidification or it may be allowed to solidify in billet or rod shape so that it can be reheated to the slurry form for further processing by techniques such as die casting.

Solid phase manufacturing processes

Powder metallurgy: Powder Metallurgy (PM) techniques have emerged as promising routes for the fabrication of

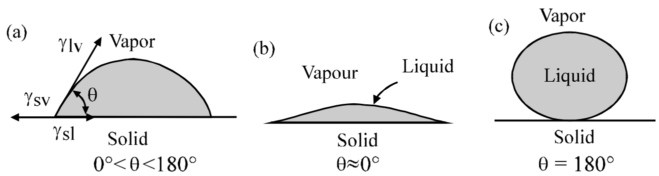

Fig. 5: Interaction of liquid droplet with solid substrate; a) partially wetting; b) completely wetting and c) completely non-wetting

particulate reinforced aluminium metal matrix composites. It is the process of blending fine powdered materials, compacting or pressing into a desired shape and then heating the material sintering to a desired shape (Shankar *et al*., 2013). Basic steps involved in powder metallurgy processing of aluminium MMCs are summarized below and shown on Fig. 5:

- Aluminium metal matrix powder production
- Blending the matrix and the reinforcement powders are blended or mixed to produce a homogeneous distribution
- Mixed powders are placed in a die and compacted by pushing a punch under pressure to produces a part called green body
- Lubricant added during blending must be driven out by low temperature heating cycle
- Baking and Sintering

Importance of powder metallurgy: Powder metallurgy has a range of diverse uses and has an important role in the advanced material processing technology industry (Skoglund *et al*., 2002):

- Efficient material utilization
- Enables close dimensional tolerances, near net shape possible to achieve
- PM process wastes very little material ~ 3%
- PM parts can be made with a specified level of porosity, to produce porous metal parts
- Difficult to fabricate parts can be shaped by powder metallurgy
- Certain alloy combinations and cermets can only be made by PM
- PM production can be automated for economical production

Limitation of powder metallurgy:

- High tooling and equipment costs
- Metallic powders are expensive
- Limitations on part geometry

WETTABILITY

Compared with monolithic materials the microstructure and the interfaces of metal matrix composite materials cannot be considered in isolation, they are mutually related (Murty *et al*., 2003). Wettability is the ability of a liquid/matrix to spread on a solid/reinforcement surface. Chemical interactions and reactions between the matrix and the reinforcement component determine the interface adhesion, modify the characteristics of the composite components and affect the mechanical characteristics significantly.

The adhesion between both phases is usually determined by the interaction between them. During the production of the molten matrix, e.g. by infiltration, wettability becomes significant (Kainer, 2006). The wettability of reinforcement with a metal melt can be shown by the edge angle adjustment of a molten droplet on a solid or reinforcement material. Itsdependent on the contact angle attained which describes the extent of intimate contactbetween a liquid and solid. The ability of a liquid to wet a solid is measured by an Eq. 3:

$$\text{Cos}\theta = \frac{\gamma sv - \gamma sl}{\gamma lv} \quad (3)$$

Where:
θ = Contact or edge angle
γsv = Solid-vapour interface
γlv = Liquid-vapor interface and
γsl = Solid-liquid interface

Wettability is inversely proportion to the contact angle, hence lower the angle, higher the contact and vice versa. Figure 6a-c shows that interaction of liquid droplet with solid substrate. Low contact angles are representative of good wetting, i.e., favorable liquid-solid interactions, whereas high contact angles greater than about 90° are indicative of poor wetting and unfavorable liquid-solid interactions (Flemings, 1991; Modi *et al*., 1988). Obviously, a favorable liquid-solid interaction is desirable in order to obtain good matrix-particles interaction.

Wettability improved based on three major parameters (Shankar *et al*., 2013; Moon *et al*., 2008). The first one is based on increasing the surface energies of the solid; the second parameter is based on decreasing the surface tension of the matrix alloy and the third parameter is based on decreasing of the solid/liquid interfacial energy. These can be improved by coating the particles with metals such as Ni and Cu or addition of active elements such as Mg into liquid aluminum or preheating of the particles before addition into liquid aluminum. Some advantages of coating particles are:

- Protect particles from environmental reaction
- Prevent direct particle-to-particle interaction
- Enhance wettability
- Relief of thermal stresses
- Protect the reinforcement during handling

Magnesium is efficient wetting agent since it fulfill the above three conditions and widely used toimprove wettability between Al and SiC particle by thinning the gas layer, i.e. by reducing the SiO_2 layer on the surface of SiC (Moon *et al*., 2008).

STRENGTHENING MECHANISMS IN PARTICLE REINFORCED ALUMINUM ALLOYS

For engineering materials design and selection, yield strength and ductility of a material are the most important parameters. These properties in MMCs are enhanced by different strengthening mechanisms (Dieter, 1988). The following mechanisms are responsible for the strengthening effect of nanoparticle addition on aluminium metal matrix composite. These are hall-petch, Orowan, load transfer, thermal mismatch and particle shearing strengthening mechanisms.

Orowan strengthening: Strengthening arising due to obstacle posed by closely-spaced hard particles to the dislocation motion. Highly dispersed reinforcements significantly increase the yield strength. The non-shearable ceramic reinforcement particles pin the crossing dislocations and promote dislocations bowing around the particles (Orowan loops) under external load (Moon *et al*., 2008; Zhang *et al*., 2004). The Orowan effect can be expressed by the following expression:

$$\Delta\sigma_{OR} = \frac{0.13Gb}{\lambda}\ln\frac{r}{b} \qquad (4)$$

Where:
G = The shear modulus
b = Burgers vector
λ = Inter particle spacing
f = is the volume fraction of particles

Table 2: Hall-Petch constant of some common metals

Metals	K (MPa $mm^{1/2}$)
Aluminium	2.16
Titanium	12.75
Iron	18.44
Copper	3.53

Inter particle spacing has been subject of many interpretation and expressed by many parameters (Moon *et al*., 2008). Simple expression for linear mean path (λ) is given by Eq. 5:

$$\lambda = \frac{4(1-f)}{3f} \qquad (5)$$

where, f is the volume fraction of spherical particles of radius r.

Hall-petch strengthening: The flow stress of a metal is almost always observed to increase as the size of its grains decreases and experimental data almost always displays a linear relationship between flow stress and the reciprocal of the square root of the grain diameter as shown in Eq. 6:

$$\sigma = \sigma_0 + \frac{K}{\sqrt{D}} \qquad (6)$$

Equation 6 is known as the hall-petch equation and the strengthening increment caused by refining the grain size is:

$$\Delta\sigma_{GB} = \frac{K}{\sqrt{D}} \qquad (7)$$

where, σ_0 and k are constants obtained from linear fitting of measured data (Table 2) and D is the average grain diameter.

Practically observed that the smaller average size of grains the more obstacles there are to dislocation motion and the higher the strength of the alloy. Nanoparticles may act as grain refiners and by doing so they contribute to the alloys strength (Zhang and Chen, 2008; Moon *et al*., 2008).

Thermal mismatch strengthening: Thermal mismatch due to the difference in the coefficient of thermal expansion between the matrix and the reinforcing particles causes plastic strain and increase the dislocation density (p) (Moon *et al*., 2008; Ham, 1969). The strengthening increment σ_{TH} may be calculated from Eq. 8:

$$\sigma_{TH} = M\beta G_m b\sqrt{p} \qquad (8)$$

$$p = \frac{A\Delta\alpha\Delta TV_p}{bd(1-V_p)} \quad (9)$$

Where:

V_p = The particle volume fraction
M = The Taylor factor
β = Contant 1.25
G = Shear modulus
b = The Burgers vector
d = The reinforcing particle diameter
$\Delta\alpha$ = The difference in the coefficient of thermal expansion between the matrix and reinforcement particles
ΔT = The difference between the processing and service temprature
A = Geometrical contant which varies between 10 and 12 on the geometry of reinforcing particles

Particle shearing strenghening: When the average diameter of the particles is very small, the applied shear stress on each particle becomes very large and the dislocations may be able to shear the precipitate particles. This process is described by the Anti-Phase Boundary (APB) mechanism (Jayalakshmi and Gupta, 2015; Hashim *et al*., 2001) where the strengthening increment, $\Delta\sigma$ABP may be calculated with Eq. 10:

$$\Delta\sigma_{ABP} = M\frac{\gamma ABP^{3/2}}{b^2}\sqrt{\frac{rf}{G}} \quad (10)$$

Load transfer strengthening: A modified Shear Lag model proposed by Nardone and Prewo (1986) (Yang, 2003) is commonly used to predict the contribution in strengthening due to load transfer in particulate reinforced composites (Zhang *et al*., 2006; Zhang and Chen, 2008).

$$\Delta\sigma_{LT} = V_p\sigma_m\left[\frac{(1+t)A}{4l}\right] \quad (11)$$

Where:

V_p = The volume fraction of the particles
σ_m = The yield strength of the unreinforced matrixand
t = The size of the particulate parallel and perpendicular to the loading direction, respectively

For the case of equiaxed particles Eq. 11 reduced to Eq. 12 according to the following (Zhang and Chen, 2008):

$$\Delta\sigma_{LT} = \frac{1}{2}V_p\sigma m \quad (12)$$

APPLICATIONS OF AL METAL MATRIX COMPOSITES

The current and potential applications of aluminium based metal matrix composites are concentrated on three specific areas: the automotive industry, the aerospace sector and the leisure market. However, interest is also growing in the field of mechanical applications mostly for wear resistant or high precision applications and in the field of electrical and electronic applications. Stiffening and strengthening of Al-alloys are receiving attention of researchers. Comparatively, particle reinforced AMMCs constitute largest quantity of composites producedand utilized on volume and weight basis (Jayalakshmi and Gupta, 2015; Ellis, 1996). The following are some potential applications of particle reinforced AMMCs:

- Used for production of fan exit guide vane (FEGV) in the gas turbine engine, as ventral fins and fuel access cover doors in military aircraft

(a)

(b)

Fig. 6: Some potential applications of AMMCs; a) brake systems of trains and b) drive shafts

- Rotating blade sleeves in helicopters
- Brake systems of trains (Fig. 6a and b)
- In automotive (Fig. 6a and b) industry which includes valves, brake systems, crankshafts, drive shafts, suspension arms, etc.
- Recreational products including golf club shaft and head, skating shoe, baseball shafts horseshoes and bicycle frames
- AMMCs containing high volume fraction ceramic particles are being used as microprocessor lids and integrated heat sinks in electronic packaging
- They are also in use as carrier plates and microwave housing, etc.

CONCLUSION

The current review reveals that extensive work has been reported to improve the properties of aluminium based MMCs reinforced with various ceramic particle materials such as: Al_2O_3, SiC and B_4C. The following major conclusion can be drawn from the present review.

The selection of appropriate processing route and process parameters during the reinforcement plays vital role for better achievement of mechanical properties of AMMCs.

Wettability between the matrix and reinforcement improved by increasing the surface energies of the solid, decreasing the surface tension of the matrix alloy and decreasing of the solid/liquid interfacial energy. The strength and ductility of particle reinforced aluminium metal matrix composite enhanced by hall-petch, orowan, particle shearing and thermal mismatch strengthening mechanisms.

Among the various types of MMCs, particle reinforced AMMCs constitutes largest quantity of composites producedand utilized in different engineering applications such as cylinder block liners, vehicle drive shafts, automotive pistons, brake systems of trains, bicycle frames, rotating blade sleeves for helicopters, etc.

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