Metal Matrix Composite Products by Vibration Casting Method

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1 Background

Industrial technology is growing at a very rapid rate and consequently there is an increasing demand for new materials. The metal/non-metal composites represent a class of materials which can withstand high temperature and pressure besides its resistance to radiation effects and chemical reactivity. Metal matrix composites can be produced by many different techniques. One of the most simplest technique is the casting process. Melting metallurgy for the production of metal matrix composite is at present of greater technical importance than powder metallurgy. It is more economical and has the advantage of being able to use well proven casting processes for the production of metal matrix composites. Metal matrix composites (MMCs) are composed of an element of alloy matrix in which a second phase is embedded and distributed to achieve some improvement in its properties. Based on the size, shape and amount of the second phase, the properties of the composite varies. Particulate reinforced composites, often called as discontinuously reinforced metal matrix composites, constitute 5–20% of these new advanced materials. The microstructure of the processed composites influences and has a great effect on the mechanical properties. Generally, increasing the volume or weight fraction of the second phase (reinforcement phase) in the matrix leads to an increased stiffness, yield strength, ultimate tensile strength and other mechanical and physical properties. But the low ductility of particulate reinforced MMCs is the major drawback that prevents their usage as structural components in some applications (Hamouda *et al.*, 1996; Rizkalla and Abdul-wahed, 1996). Miller and Humphreys (1991a) have carried out a detailed investigation on the strengthening mechanism of composites. They have found that the particle size and its volume fraction in metal matrix composites influence the generation of dislocations due to thermal mismatch as well as the effect influenced by the developed residual and internal stresses. The researchers have predicted that the dislocation density is directly proportional to the volume fraction and also due to the amount of mismatch. The resulting strengthening effect (quench strength) is proportional to the square root of the dislocation density. Consequently, this effect would be significant for fine particles and for higher volume fractions. Recent studies have shown that the matrix microstructure has a clear effect on the fracture details of the tested specimen.

The mechanical properties and microstructure of aluminum/TiC MMCs have been compared between three processes namely powder processing (PM), flux-casting process, and melting PM material. In cast, particle clustering is more prevalent than PM composites, but in cast MMCs, the degree of clustering reduced by the grain-refining nature of TiC particles while oxide films in melting PM material trawled the particles into large clusters. Cast and PM composites have the similarity in stiffness and ductility but strength and ductility significantly reduced when melting the PM material and for all cases, removal of porosity and the break-up of particle clusters by extrusion will enhance composite ductility. Indication by modulus measurements as a function of plastic strain in cast composites consequently of the attainment of intimate contact and strong chemical bonding between the two phases show rate of damage accumulation are lowest thus interfacial bonding is strongest (Kennedy and Wyatt, 2000).

Limmaneevichitr *et al.* (2009) investigated the effects of mechanical vibration during solidification on the metallurgical structure of hypoeutectic aluminum–silicon A356. Emphasis was placed on the morphological changes of the primary aluminum phase of the as-cast alloy, which was subjected to different levels of mechanical vibration at various values of pouring temperature and solid fraction. They found that the average grain size of the primary phase became relatively finer and more globular as the degree of vibration were increased. This suggested that during the solidification process, dendrites that formed normally in the liquid alloy were subsequently disturbed and fragmented by the mechanical vibration applied into the melt. This effect was enhanced when the vibration was applied into an alloy with a larger solid fraction, as was observed with solidification at lower pouring temperatures. In addition to the macrostructure examination, semi-solid properties were also assessed and reported using the Rheocasting Quality Index (RQI). It was shown that the application of mechanical vibration into the A356 melt with adequate solid fraction prior to complete solidification successfully resulted in an as-cast structure featuring semi-solid morphology.

Vibration of a solidifying metal is an old process that was developed early in the last century to assist the casting of aluminum alloys (Mohanty and Gruzleski, 1995). Vibration has been used to help in the promotion of nucleation and thus reducing as-cast grain size, lower susceptibility to cracking and reducing shrinkage porosities which leads to improved features and thereby improved mechanical properties (Shukla *et al.*, 1980; Sayuti *et al.*, 2014). Usually, a known frequency and amplitude of sinusoidal vibration is applied using a vibration mould during the solidification process. The various types of vibration such as mechanical, ultrasonic or electromagnetic vibration may be applied to the metal through different means. The mechanical vibration may be introduced to the entire mold with the solidifying metal inside of it or it may be limited to the solidifying metal only, while the use electromagnetic vibration can only be applied to the solidifying metal (Numan *et al.*, 2005).

Applying mechanical mould vibration during the solidification process is a very simple technique that does not require complicated procedure neither needs expensive set-up (Sayuti *et al.*, 2012a,b,c). It can be applied for the current existing processes and does not require extensive modifications on the design of the used equipments. It requires less energy as compared to ultrasonic vibration, electromagnetic vibration and semisolid processes and also less expensive. The low energy requirement during the chemical-process made it the most environmentally-friendly process than any other grain refinement technique. There are three practicable methods for application of vibration, namely, mechanical vibration of the whole of the mould, vibration of the liquid solidifying metal, and electromagnetic induction (Kocatepe and Burdett, 2000).

Electromagnetic vibration technique is one of the non-contact methods used to induce vibration inside the solidifying metal. The vibration is induced by applying an orthogonal static magnet and alternating electric fields. It was reported that the collapse of the cavities generated by this method was responsible for the grain refinement of the microstructure for Al–7%Si, Al–17%Si, and gray cast iron (Vives, 1988). However, it was also reported that this method is costly and requires tremendous amount of current to be effective (Radjai and Miwa, 2000). On the other hand, application of mechanical vibration during solidification is more commonly used than electromagnetic vibration and another vibration technique due to its simplicity and low cost (Maltais *et al.*, 2003).

Application of the electromagnetic vibration during the casting led to significant grain refinement that greatly reduced segregation in the billet. There was a significant increase in mechanical properties such as the tensile strength, hardness, and fracture elongation of the as-cast AZ80 billet relative to that cast in the absence of the electromagnetic vibration. Microchemical analysis revealed that the application of electromagnetic vibration can be increased concentration of Al and Zn in the Mg matrix (Guo *et al.*, 2006).

However, a review of the literature reveals that the application of mechanical, electromagnetic and ultrasonic vibration has a number of notable effects such as grain refinement, increased density, hardness, ultimate tensile strength, percent elongation, degassing, shrinkage, and the shape, size and distribution of the second phase (Alireza and Miwa, 2000; Eskin, 2001; Swamy *et al.*, 2008). Vibration energy has been applied in many processes within the metallurgical and engineering fields (Kocatepe, 2007; Sayuti *et al.*, 2012a,b,c). According to the review by Feng-Wuan and Xiao-Ling (2000), the application of vibration during solidification was first studied in 1800s.

2 Metal Matrix Composites (MMCs)

2.1 General

Metal matrix composites are classified under advanced engineering materials which consists of two or more materials, where tailored properties can be attained by systematic combination of different metallic or non-metallic constituents (Kalpakjian, 1995). Wide varieties of methods are available for metal matrix composites processing including the conventional metal casting process (Amstead *et al.*, 1987; Sayuti *et al.*, 2012a,b,c). The advantages of composite preparation by casting technology are its near-net shape manufacturing which is a cost-effective and simple method (Chadwick, 1990; Ibrahim *et al.*, 1991). Addition to this, casting processes are employed to manufacture large number of complicated composite casting components at a faster rate required by the aerospace, automobile, transportation, sports and consumer-oriented industries.

Fabrication of discontinuously reinforced Al-based MMCs can be achieved by standardized metallurgical processing methods like powder metallurgy, direct casting, rolling, forging and extrusion. Furthermore the products can be shaped, machined and drilled by using conventional machining facilities. Thus, they can be made available in suitable quantities particularly for automotive applications (Seah *et al.*, 2003).

According to Ejiofor and Reddy (1999) and Hashim *et al.* (2002a), metal matrix composites (MMC) represent a new generation of engineering materials in which a strong ceramic reinforcement is incorporated into a metal matrix to improve its properties including elastic modulus, specific strength, specific stiffness, wear resistance and corrosion resistance. MMCs combine metallic properties of matrix alloys (ductility and toughness) with ceramic properties of reinforcements (high strength and high modulus), hence leading to a greater strength in shear and compression and higher service-temperature capabilities. Thus, they have significant scientific, technological and commercial importance. During the last decade, as a result of their improved properties, MMCs are being used extensively for high performance applications such as in automotive industries and more recently in the aircraft engines (Pank and Jackson, 1993; Taufik *et al.*, 2011a).

Aluminum oxide and silicon carbide powders in the form of fibers and particulates are commonly used as reinforcements in MMCs and the addition of these reinforcements to aluminum alloys has been subjected to an extensive amount of research work. Aluminum oxide and silicon carbide reinforced aluminum alloy matrix composites are applied in aircraft industries as engine pistons, cylinder heads and automotives, where the tribological properties of these materials are considered important (Kim *et al.*, 2005; Ponzi, 1992). Incorporation of hard second phase particles in the alloy matrices to produce MMCs has also been reported to be more beneficial and economical due to its high specific strength and corrosion resistance properties. Metal matrix composites are materials that are attractive for a large range of engineering applications (Kok, 2005; Sayuti *et al.*, 2011a,b,c,d,e).

Premkumar and Chu (1995) used an situ process to produce fine TiC particulates in a molten aluminum alloy. Introducing carbonaceous gas into an Al melt containing Ti formed TiC particulates. The determination of the carbide volume fraction is by the initial Ti content. For microstructure and property evaluation, the melt containing the carbides was cast and then extruded the microstructure of the in situ processed composites reveals a relatively uniform distribution of TiC particles with an average size of a few microns. The effect of the particles in increasing the yield strength of the composites is more clearly illustrated by comparing the composites ($V_f = 0.064$) with the unreinforced control sample; the particle-containing alloy has a higher yield strength despite having no stretch prior to ageing. The sub-micron sized fine particles of TiC that are present in these composites are believed to contribute to strengthening factor, the elastic modulus of the base alloy will increase the by 14%. However, the higher density of TiC results in a 4.5% increase in density of the composite over the base alloy. Thus, on a specific modulus basis (elastic modulus or density), there is an increase of $\sim$9% with the addition of TiC ($V_f = 0.064$).

The *in situ* fabrications by SHS reaction of the Al–Ti–C system during aluminum melt casting cause TiC particulates locally reinforced Al–matrix composites (Tong and Fang, 1998). The adiabatic temperature was lowered and ignition delay time was prolonged due to the increasing of Al contents in the green compacts. For 20–40 wt% Al contents in the blends, there are only two phases, TiC and α-Al, can be observed. But in the case of 10 or 50 wt% Al content, the self-heat-sustained (SHS) reaction cannot be initiated. Further X-ray diffraction (XRD) and Differential scanning calorimetric (DSC) studies revealed that the aluminum acts as an intermediate reactant participating in the reaction and not only as diluents. When adding 10 wt% of Al content in the compact, the heat released from the intermediate reaction of Ti–Al is too low to induce the further reaction to form TiC. The interfaces between the Al–matrix and the locally reinforced region with the in-situ formed TiC particulates uniformly distributed showed excellent gradient and bonding. The size of TiC particulates decreased sharply from about 1.0 to 0.2 μm with increasing Al contents from 20 to 40 wt% (Song *et al.*, 2008; Taufik *et al.*, 2011b).

Al–TiC metal matrix composites have been produced by a novel route which enables the nucleation of solid Al on the TiC reinforcing phase to occur and results in line as-cast grain sizes (Tong and Fang, 1998; Taufik *et al.*, 2011c). Solid nucleation results in extensive grain refinement and the engulfment of more particles into the growing primary Al grains during solidification. The 0.2% proof and UTS of CP Al–TiC composites consistently increased as more particles of TiC are added (**Table 1**). Large proof stress increase suggest that the TiC particles contribute significant strengthening to the composite beyond that due to grain size reduction. The fractional decrease in ductility increases as the strength of the matrix is increased, suggesting that the debonding behavior is stress dominated. Stiffness increases per volume percent of reinforcement added are higher for TiC than that of SiC and Al_2O_3 despite TiC being the least stiffness reinforcing phase. The nucleation of solid on the reinforcing phase results in strong particle–matrix bonding and efficient load transfer thereby maximizing modulus improvements and minimizing decreases in ductility (Kaftelen *et al.*, 2011; Karantzalis *et al.*, 1997). The tensile strength and yield strength increased up to 18% after the formation of TiC in the Al alloy matrix while the hardness increased by up to 20% (**Table 2**). The *in situ* formation of TiC particles increases the abrasive and sliding wear resistance (Shyu and Ho, 2006). Methods used for manufacturing the Al–10 vol% TiC composites are summarized in (**Table 3**; Kennedy and Wyatt, 2001).

Table 1 Mechanical properties of CP Al–TiC extruded composite with various particle additions

Reinforcements (vol%)	*Modulus (GPa)*	*0.2% Proof stress (MPa)*	*UTS (MPa)*	*Elongation (%)*
0	69 ± 0.5	70 ± 3	89 ± 3	33 ± 3
10	85 ± 0.5	103 ± 5	127 ± 7	22 ± 2
15	92 ± 0.5	111 ± 6	140 ± 9	12 ± 1
18	98 ± 0.5	128 ± 4	163 ± 5	8 ± 1

Source: Karantzalis *et al.*, 1997.

Table 2 Samples of tensile strength and hardness data

Sample	*UTS (MPa)*	*YS (MPa)*	*Hardness (HB)*	*Modulus (GPA)*
Al–5.1Cu–6.2Ti (alloy)	330 ± 12	262 ± 6	94 ± 4	78 ± 4
Composite	400 ± 15	296 ± 8	114 ± 5	94 ± 5

Source: Shyu and Ho, 2006.

Table 3 Processing of the Al–10 vol% TiC composites

Process	*Code*	*Condition*
TiC powders added tomolten Al using a flux,cast into metal molds	CAST	Added at 8008 °C and held for 10 min in molten state
Tumble blended Al/TiC powders, hotisostatically pressed toconsolidate	PM-HIP	HIPed at 125 MPa, at 5808 °C for 2 h
Mechanically alloyedAl/TiC powders, hotisostatically pressed toconsolidate	PM-MA	HIPed at 125 MPa, at 5808 °C for 2 h
Tumble blended Al/TiC powders, canned,cold compacted,extruded at slow ramspeed	PM-EXT_S	Extruded at 4008 °C, $R = 13$: 1; at 0.5 mm s^{-1}
Tumble blended Al/TiC powders, canned,cold compacted,extruded at fast ramspeed	PM-EXT_F	Extruded at 4008 °C, $R = 13$: 1; at 1.0 mm s^{-1}

Source: Kennedy and Wyatt, 2001.

2.2 Classification of Composites

Among the major developments in materials in recent years are composite materials. In fact, composites are now one of the most important classes of engineered materials, because they offer several outstanding properties as compared to conventional materials. The matrix material in a composite may be ceramic based, polymer or metal. Depending on the matrix, composite materials are classified as follows:

a) Metal matrix composites (MMCs)
b) Polymer matrix composites (PMCs)
c) Ceramic matrix composites (CMCs)

Majority of the composites used commercially are polymer-based matrices. However, metal matrix composites and ceramic matrix composites are attracting great interest in high temperature applications (Feest, 1986). Another class of composite material is based on the cement matrix. Because of their importance in civil engineering structures, considerable effort is being made to develop cement matrix composite with high resistance to cracking (Schey, 2000). The common matrix materials used in composite are listed in **Table 4**.

Metal matrix composites (MMCs) are composites with a metal or alloy matrix. It has resistance to elevated temperatures, higher elastic modulus, ductility and higher toughness. The limitations are higher density and greater difficulty in processing parts. Matrix materials used in these composites are usually aluminum, magnesium, aluminum–lithium, titanium, copper and super alloys. Fiber materials used in MMCs are aluminum oxide, graphite, titanium carbide, silicon carbide, boron, tungsten and molybdenum. The tensile strengths of non-metallic fibers between 2000 and 3000 MPa, with elastic modulus being in the range from 200 to 400 GPa. Because of their lightweight, high specific stiffness and high thermal conductivity, boron fibers in an aluminum matrix have been used for structural tubular supports in the space shuttle orbiter. Metal matrix composites having silicon carbide fibers and a titanium matrix are being used for the skin, stiffeners, beams and frames of the hypersonic aircraft under development. Other applications are in bicycle frames and sporting goods (Wang *et al.*, 2006). Graphite fibers reinforced in aluminum and magnesium matrices are applied in satellites, missiles and in helicopter structures. Lead matrix composites having graphite fibers are used to make storage-battery plates. Graphite fibers embedded in copper matrix are used to fabricate electrical contacts and bearings. Boron fibers in aluminum are used as compressor blades and structural supports. The same fibers in magnesium are used to make antenna structures. Titanium-boron fiber composites are used as jet-engine fan blades. Molybdenum and tungsten fibers are dispersed in cobalt-base superalloy matrices to make high temperature engine components. Squeeze cast MMCs generally have much better reinforcement distribution than compocast materials. This is due to the fact that a ceramic preform is used contains the desired weight fraction of reinforcement rigidly attached to one another so that movement is inhibited. Consequently, clumping and dendritic segregation are eliminated. Porosity is also minimized, since pressure is used to force the metal into interfiber channels, displacing the gases. Grain size and shape can vary throughout the infiltrated preform because of heat flow patterns. Secondary phases typically form at the fiber-matrix interface, since the lower freezing solute-rich regions diffuse toward the fiber ahead of the solidifying matrix (Surappa, 2003; Sayuti *et al.*, 2011a,b,c,d,e).

Ceramic matrix composites (CMCs) are composites with a ceramic matrix are another important development in engineered materials because of their resistance to corrosive environments and high temperatures. Ceramics are strong and stiff, and they resist high temperatures, but they generally lack toughness. Matrix materials that retain their strength up to 1700 °C are silicon nitride,

Table 4 List of common matrix materials used in composites application

Polymeric based composites	● **Thermoset resins** Epoxies: Principally used for aerospace, aircraft, and sporting goods manufacturing applications Polyesters and vinyl esters: Principally used for automotive, marine, chemical, electrical and consumer goods applications Polyurethanes and polyurea: Principally used in reaction injection molding process for manufacturing automotive body parts Phenolics: Used in both aerospace and automotive applications ● **Thermoplastics** Nylon 6, thermoplastic polyesters such us PET and PBT, polycarbonate, polyacetals, polypropylene: reinforced withdiscontinuous fibers in injection-molded articles Polyether ether ketone (PEEK), polyphenylene sulfide (PPS), polysulfone (PSUL), polyamide-imide (PAI), polyether imide (PEI), etc.: Used with both continuous and discontinuous fibers for moderately high-temperature applications
Metal matrix composites	Aluminum alloys, titanium alloys, magnesium alloys, copper-based alloys, nickel-based alloys: mostly used for moderately high-temperature applications
Ceramic matrix composites	Silicon carbide, titanium carbide, aluminum oxide, silicon nitride, carbon: used for high-temperature applications

Source: Schey, 2000.

silicon carbide, aluminum oxide, and mullite (a compound of aluminum, silicon, and oxygen). Carbon–carbon matrix composites retain much of their strength up to 2500 °C, although they lack oxidation resistance at high temperatures. Carbon–carbon fiber composites are probably the most highly developed of the ceramic matrix composites. These materials are developed mainly used as brake materials for the aerospace industry. Such composites are produced by impregnating shaped carbon or graphite fibers with a carbonized precursor which is subsequently pyrolized, or by chemical vapor decomposition of carbon or graphite. The resulting materials are strong and light weight, and have excellent high temperature properties, good corrosion resistance, and good thermal shock, electrical, and wear characteristics (Windhorst and Blount, 1997). Their ease of forming makes them useful for wide spread applications. Carbon–carbon fiber CMCs are used as thermal insulation materials, as electrodes, bearings, disks, brake linings, screws and gaskets, nuclear reactor parts, seals, foundry molds, gas turbines, and in pistons for engines. Aerospace applications of such composites are as brakes, rocket nozzles, re-entry systems, turbine blades, rocket exhaust systems, and as heat shields (Kalpakjian, 1995). Fiber materials are usually carbon and aluminum oxide. Various techniques for improving the mechanical properties of ceramic–matrix composites, particularly their toughness, are being investigated. Applications are in jet and automotive engines, deep-sea mining equipment, pressure vessels, structural components, cutting tools, and dies for the extrusion and the drawing of metals (Humphreys, 1987).

2.3 Significance of Composites

Composites technology and science requires loose interaction of various disciplines such as structural analysis and design, mechanics of materials, materials science and process engineering. The tasks of composites research are to investigate the basic characteristics of the constituents and composite materials, develop effective and efficient fabrication procedures, optimize the material for service conditions and understanding their effect on material properties and to determine material properties and predict the structural behavior by analytical procedures and hence to develop effective experimental technique for material characterization, failure analysis and stress analysis (Daniel and Ishai, 1994; Sayuti *et al.*, 2011a,b,c,d,e). An important task is the non-destructive evaluation of material integrity, durability assessment, structural reliability, flaw criticality and life prediction. New types of carbon fibers are being introduced with higher ultimate strains (Ganesh and Chawla, 2005). Thermoplastic matrices are used under certain circumstances because they are tough and have low sensitivity to moisture effects and are more easily amenable to mass production and repair. The use of woven fabric and short fiber reinforcement is receiving more attention. The structures design and systems capable of operating at elevated temperatures has spurred intensive research in high temperature composites, such as ceramic/matrix, metal/ceramic and carbon/carbon composites. The utilization of conventional and new composite materials is intimately related to fabrication methods development. The manufacturing process is one of the most important stages in controlling the properties and ensuring the quality of the finished product. The technology of composites, although still developing has reached a state of maturity. Prospects for the future are bright for a variety of reasons. Newer high volume applications, such as in the automotive industry, will expand the use of composites greatly.

2.4 Preparation of MMCs

Metal matrix composite materials can be produced by various methods. The focus on the selection of suitable engineering process is to achieve the desired kind, distribution and quantity of the reinforcement components (fibers and particles), the matrix alloy and the applications. By altering the manufacturing method, the processing and the finishing, as well as by the form of the reinforcement components, it is possible to obtain different characteristic profiles, although the same composition and amounts of the components are involved (Girot *et al.*, 2003). The production of a suitable precursor material, the processing to a construction unit or a semi-finished material (profile) and the finishing treatment must be separated. For cost effective reasons prototypes, reforming procedures are used and with dimensions close to the final product which can minimize the mechanical finishing of the construction units (Kainer, 2006). In general the following engineering process types are possible:

a) Melting metallurgical processes
b) Hot isostatic pressing of powder mixtures and fiber clutches
c) Powder metallurgical processes
d) Further processing of precursor material from the melting metallurgy by thixocasting or -forming, extrusion, forging, cold massive forming or super plastic forming
e) Joining and welding of semi-manufactured products
f) Combined deformation of metal wires (group superconductors).
g) Finishing by machining techniques.

Melting metallurgy for the production of MMCs is at present of greater technical importance than powder metallurgy (Hashim *et al.*, 2001; Kainer, 2006). It is more economical and has the advantage of being able to use well proven casting processes for the production of MMCs. For melting metallurgical processing of composite materials three procedures are mainly used (Kainer, 2006):

a) Compo-casting or melt stirring: Both the terms compo-casting and melt stirring are used for stirring particles into a light alloy melt.
b) Squeeze casting or pressure casting: Squeeze casting is a process by which molten metal solidifies under pressure within closed dies positioned between the plates of a hydraulic press.
c) Gas pressure infiltration: In gas pressure infiltration the melt infiltrates the preform with a gas applied from the outside. A gas that is inert with respect to the matrix is used.

3 Matrix or Matrices

Matrix is the percolating alloy/metal/polymer/plastic/resin/ceramic forming the constituent of a composite in which other constituents are embedded. If the matrix is a metal, then it is called as a metal matrix and consecutively polymer matrix, if the matrix is a polymer and so on. In composites, the matrix or matrices have two important functions (Weeton *et al.*, 1988). Firstly, it holds the reinforcement phase in the place. Then, under an applied force, it deforms and distributes the stress to the reinforcement constituents. Sometimes the matrix itself is a key strengthening element. This occurs in certain metal matrix composites. In other cases, a matrix may have to stand up to heat and cold. It may conduct or resist electricity, keep out moisture, or protect against corrosion. It may be chosen for its weight, ease of handling, or any of many other applications. Any solid that can be processed to embed and adherently grip a reinforcing phase is a potential matrix material. Polymers and metals have been very successful in the role and inorganic materials such as glass, Portland cement, plaster, carbon, and silicon have been used as matrix materials with varying success. These later materials remain elastic up to their points of failure and characteristically exhibit low failure strains under tensile loading, but are strong under compression. One important consideration of matrix in composite production is how the constituents of a composite interact during fabrication and/or use (Sulaiman *et al.*, 2008). They should not react chemically or metallurgically in a way that harms. In general, they should not have greatly different coefficients of linear thermal expansion. The area of contiguous contact between the matrix and the reinforcing material is called the interface, which in some ways is analogous to the grain boundaries in monolithic materials. In certain cases, however, the contiguous region is a distinct added phase, called an interphase. Examples are the coating on the glass fibers in reinforced plastics, and the adhesive that bonds the layers of a laminate together. When such an interphase is present, there are two interfaces – one between each surface of the interphase and its adjoining constituent. In still other composites, the surfaces of the dissimilar constituents interact to produce an interphase. Fabrication methods depend to a great degree on the matrix properties, and how the matrix affects the properties of the reinforcements. Some of the important matrices used normally in composites processing are metal, polymer, ceramic, glass, and carbon/graphite.

In a composite, matrix is an important phase, which is defined as a continuous one. The important function of a matrix is to hold the reinforcement phase in its embedded place, which act as stress transfer points between the reinforcement and matrix and protect the reinforcement from adverse conditions (Clyne, 1996). It influences the mechanical properties, shear modulus and shear strength and its processing characteristics. Reinforcement phase is the principal load-carrying member in a composite. Therefore, the orientation, of the reinforcement phase decides the properties of the composite.

4 Reinforcing Phase/Materials

Reinforcement materials must be available in quantity and at an economical rate. Recent researches are directed towards a wider variety of reinforcements for the range of matrix materials being considered, since different reinforcement types and shapes have specific advantages in different matrices (Basavarajappa *et al.*, 2004). It is to be noted that the composite properties depend not only on the properties of the constituents, but also on the chemical interaction between them and on the difference in their thermal expansion coefficients, which both depend on the processing route. In high temperature composites, the problem is more complicated due to enhanced chemical reactions and phase instability at both processing and application temperature. Reinforcement phases in MMCs are embedded in the form of continuous reinforcement or discontinuous reinforcement in the matrix material. Continuous reinforcement phase is continuous in at least one direction through the composite. Continuous fibers or percolating open-celled foam is suitable examples of the continuous reinforcement phase type. Continuous fibers are cylindrical ingredient material produced continuously to form an essentially endless reinforcement in the composite, usually delivered on bobbins of multifilament tows, each tow consisting of many individual fibers of diameters typically in the range of 3–30 μm. According to the production process, such fibers are usually coated by a polymeric sizing and the tows may be slightly twisted. They are typically designated by a brand name, the number of fibers per tow and a symbol of the applied sizing. Monofilaments are endless reinforcement as continuous fibers, except for a larger diameter, typically greater than 100 μm. Monofilaments are generally produced by deposition onto a core fiber and are delivered as individual fibers instead of tows. Discontinuous reinforcement is a non-percolating constituent of a composite, taking the form of individual elements embedded in the matrix constituent as particulates, short fibers, and whiskers. Preforms produced from discontinuous reinforcements that are mechanically stabilized by a binder or by cold compaction are still considered discontinuous reinforcements (Attia, 2001). Particulates are roughly equiaxed reinforcement, usually of aspect ratio less than about 5. They can be both mono- and polycrystalline, can take various shapes like spherical, angular, and plate-like and are typically greater than 1 μm in diameter. Dispersoids are the same as particulates, except that the diameter is less than 1 μm, hence, being capable of providing strengthening. Platelets are flat reinforcements of an aspect ratio (diameter to thickness) greater than two. Platelets of an aspect ratio less than 5 can be considered as a type of particulate. Short fibers are cylindrical reinforcements with a ratio of length to diameter greater than 5, but typically greater than 100, and with a diameter typically greater than 1 μm. Whiskers are elongated single crystals, typically produced with a length to diameter ratio greater than 10 and with a diameter typically less than 1 μm. Several refractory reinforcing phases are used in composites processing. They are refractory metals, carbides, nitrides, borides, oxides, sulfides, intermetallics, silicides, and silicates. Since refractory metal compounds such as carbides, nitrides, borides, silicide and oxides are known to be extremely hard and to keep their strength at elevated temperatures (Ibrahim *et al.*, 1991). There are different considerations in choosing reinforcement. The selecting criteria must be set up based on their properties, which are mainly influenced by the chemical composition, melting point, density, volume shrinkage, shape and size, crystal structure, free energy of formation, Young's modulus, diffusivity and finally, availability, ease of production and use. A large number of different oxides, carbides, nitrides and borides are suitable for reinforcement; an overview is given in **Table 5** (Kainer, 2006). The following have proved technically and economically interesting: silicon and boron carbides, aluminum oxide, aluminum and boron nitrides and titanium boride. A summary of the properties of these hard materials is given in **Table 6**.

The reinforcing phase may be a particulate or a fiber, continuous type or discontinuous type. Some of the important particulates normally reinforced in composite materials are titanium carbide, tungsten carbide, silicon nitride, aluminum silicate, quartz, silicon carbide, graphite, fly ash, alumina, glass fibers, titanium boride, etc. The reinforcement second phase material is selected depending on the application during the processing of composites (Clyne, 1996). The reinforcement phase is in the form of particulates and fibers generally. The size of the particulate is expressed in microns, micrometer. However, the discontinuous fiber is defined by a term called as 'Aspect Ratio'. It is expressed as the ratio of length to the diameter of the fiber. To improve the wettabilty with the liquid alloy or metal matrix material, the reinforcement phase is always preheated (Adams *et al.*, 2003; Sayuti *et al.*, 2011a,b,c,d,e). Some potential composite-reinforcement materials and their applications are listed in **Table 7**.

Table 5 Potential particle for metal reinforcement

Metal-basis	*Carbide*	*Nitride*	*Boride*	*Oxide*
Boron	B_4C	BN	–	–
Tantalum	TaC	–	–	–
Zirconium	ZrC	ZrN	ZrB_2	ZrO_2
Hafnium	HfC	HfN	–	HfO_2
Aluminum	–	AlN	–	Al_2O_3
Silicon	SiC	Si_3N_4	–	-
Titanium	TiC	TiN	TiB_2	–
Chromium	CrC	CrN	CrB	Cr_2O_3
Molybdenum	Mo_2C, MoC	Mo_2N, MoN	Mo_2B, MB	
Tungsten	W_2C, WC	W_2N, WN	W_2B, WB	
Thorium	–	–	–	ThO_2

Source: Kainer, 2006.

Table 6 Properties of various particles for reinforcement of metals

Type of particle	*SiC*	*Al_2O_3*	*AlN*	*B_4C*	*TiB_2*	*TiC*	*BN*
Type of crystal	Hex.	Hex.	Hex.	Rhomb.	Hex.	Cub	Hex.
Melting point [°C]	2300	2050	2300	2450	2900	3140	3000
Young's modulus [GPa]	480	410	350	450	370	320	90
Density [gm cc^{-1}]	3.21	3.9	3.25	2.52	4.5	4.93	2.25
Heat conductivity [W m^{-1} K^{-1}]	59	25	10	29	27	29	25
Mohs-hardness	9.7	6.5	–	9.5	–	–	1.0–2.0
Thermal coefficient of expansion [10^{-6} K^{-1}]	4.7–5.0	8.3	6.0	5.0–6.0	7.4	7.4	3.8

Source: Kainer, 2006.

Table 7 Some potential composite-reinforcement phase/materials and applications

Metal base	*Carbides*	*Nitrides*	*Borides*	*Oxides*	*Applications*
Boron	B_4C	BN	_	_	Aerospace, nuclear
Tantalum	TaC	TaN	TaB_2	_	Aerospace
Zirconium	ZrC	ZrN	ZrB_2	ZrO_2	Aerospace, automotive, nuclear
Hafnium	HfC	HfN	HfB	HfO_2	Aerospace, nuclear
Aluminum	_	AlN	_	Al_2O_3	Automotive, metal working
Silicon	SiC	Si_3N_4	_	_	Automotive, aerospace, metal working
Titanium	TiC	TiN	TiB_2	_	Aerospace
Chromium	CrC	_	CrB_2	CrO_2	Aerospace, Automotive
Molybdenum	MoC	_	MoB	_	Aerospace, automotive
Tungsten	WC	–	WB	–	Metal working
Thorium	ThC_2	ThN	–	ThO_2	Aerospace

Source: El-Mahallawy and Taha, 1993.

4.1 Factors Affecting Reinforcement

The interface between the matrix and the reinforcement plays an important role for deciding and explaining the toughening mechanism in the metal matrix composites. The interface between the matrix and the reinforcement should be organized in such a way that the bond in between the interface and the matrix should not be either strong or weak (Singh *et al.*, 2001).

4.2 Matrix Interface/Interphase of Matric

Interfaces are considered particularly important in the mechanical behavior of MMCs since they control the load transfer between the matrix and the reinforcement. Their nature depends on the matrix composition, the nature of the reinforcement, the fabrication method and the thermal treatments of the composite. For particular matrix/reinforcement associations and especially with liquid processing routes, reactions can occur which change the composition of the matrix and lead to interfacial reaction products, thus changing the mechanical behavior of the composites. The interfacial phenomena in MMC have been surveyed by several authors. Considering physical and chemical properties of both the matrix and the reinforcing material, the actual strength and toughness desired for the final MMCs, a compromise has to be achieved balancing often several conflicting requirements. A weak interface will lead to crack propagation following the interface, while a strong matrix associated with a strong interface will reveal cracks across both the matrix and the reinforcements. If however the matrix is weak in comparison with the interface and the particle strength, the failure will propagate through the matrix itself. The wettability of the reinforcement material by the liquid metallic matrix plays a major role in the bond formation. It mainly depends on heat of formation, electronic structure of the reinforcement and the molten metal temperature, time, atmosphere, roughness and crystallography of the reinforcement. Similarity between metallic bond and covalent bond is reflected in some metal, like titanium carbide and zirconium carbide which are more easily wetted than strong ionic bonds found in ceramics such as alumina that remains poorly wetted. Surface roughness of the reinforced material improves the mechanical interlocking at the interface, though the contribution of the resulting interfacial shear strength is secondary compared to chemical bonding. Large differences in thermal expansion coefficient between the matrix and the reinforcement should be avoided as they can include internal matrix stresses and ultimately give rise to interfacial failures. From a purely thermo dynamical point of view, a comparison of free enthalpy of formation at various temperatures shows that many metals in the liquid state are reactive toward the reinforcing materials in particular oxides or carbides. Though thermodynamically favoured, some reactions are however not observed and practically the kinetics of these reactions has to be considered in conjunction with thermodynamic data in order to evaluate the real potential of the reactions. The consequences of such interfacial reactions are the chemical degradation of the reinforcing material associated with a decrease of its mechanical properties, the formation of brittle reaction products at the interface, as well as the release of elements initially part of the reinforcing material toward the matrix may generate inopportune metallurgical phases at the vicinity of the reinforcing materials. Moreover in the case of alloyed matrices, the selective reactivity and depletion of given elements from the alloy can generate compositional gradients in the matrix and may therefore alter its properties close to the interface. Though a moderate reaction may improve the composite bonding, extended reactions usually ruin the reinforcing material. The relation between interfacial reactions and interface strength depends on the materials. The elaboration of MMC requires often a very short solidification time to avoid excess interfacial reaction. During the cooling process, differences in thermal capacity and thermal conductivity between the reinforcing material and the matrix induce localized temperature gradients. Solidification of the metallic matrix is believed to be generally a directional outward process, starting from the inside of the metallic matrix while ending at the reinforcing material surface. Finally, the processing type and the parameters have to be selected and adjusted to a particular MMC system. Metals are generally more reactive in the liquid rather than in the solid state. Consequently, shorter processing time, that is, short contact time between the liquid metal and the reinforcement can limit the extent of interfacial reactions. The study of reinforcement and matrix bonding is important in composite matrix structure, which has been described by Gregolin *et al.* (2002). While the load is acting on the composite, it has been distributed to the matrix and the reinforcement phase through the matrix interface. The reinforcement is effective in strengthening the matrix only if a strong interfacial bond exists between them. The interfacial properties also influence the resistance to crack propagation in a composite and therefore its fracture toughness (Dusza and Sajgalik, 1995). The two most important energy-absorbing failure mechanisms in a composite are debonding and particle pull out at the particle matrix interface. If the interface between the matrix and reinforcement debonds, then the crack propagation is interrupted by the debonding process and instead of moving through the particle, the crack move along the particle surface allowing the particle to carry higher load (El-Mahallawy and Taha, 1993).

4.3 Chemical Reaction

The Al and TiC reaction has not yet been clearly established. Because of two materials are not in equilibrium when in contact Al between TiC. There are three reactions of Al and TiC have been proposed (Daniel and Ishai, 1994; Sahoo and Koczak, 1991).

$$4\mathrm{Al(1)} + 3\mathrm{TiC(s)} = \mathrm{Al_4C_3(s)} + 3\mathrm{Ti(1)} \quad [1]$$

$$\text{or,} \quad \mathrm{Al} - \mathrm{Ti} + \mathrm{CH_4} = \mathrm{Al_4C_3(s)} + \mathrm{Al} + \mathrm{TiC} \quad [2]$$

$$7\mathrm{Al} + 3\mathrm{TiC} = \mathrm{Al_4C_3} + 3\mathrm{TiAl} \quad [3]$$

$$13\mathrm{Al} + 3\mathrm{TiC} = \mathrm{Al_4C_3} + 3\mathrm{TiAl_3} \quad [4]$$

The free energy change at different temperatures for these three reactions between Al and TiC are shown in **Figure 1**. Note that only the reaction of Al_4C_3 form and $TiAl_3$ (Reaction [4]) is feasible and this is only true for temperatures below 750 °C, approximately. Other has quote similar free energies for these reactions.

During Al/TiC composites processing, a number of phases have been reported. The Al_4C_3 and $TiAl_3$ is a most common presence, which would be understandable according to eqn [4]. This include TiAl (probably through the reaction eqn [3] to be thermodynamically unstable) and ternary compounds such as Ti_2AlC (H phase) and the Perovskite phase Ti_3AlC. These latter two may form through secondary reaction (Daniel and Ishai, 1994):

$$\mathrm{TiAl} + \mathrm{TiC} = \mathrm{Ti_2AlC} \quad [5]$$

$$\mathrm{Ti_3Al} + \mathrm{TiC} = \mathrm{Ti_3AlC} + \mathrm{Ti} \quad [6]$$

The formation of these phases, especially at room temperature, is not yet fully understood since thermodynamic data is not available for such compounds. Therefore eqns [5] and [6] are only speculative.

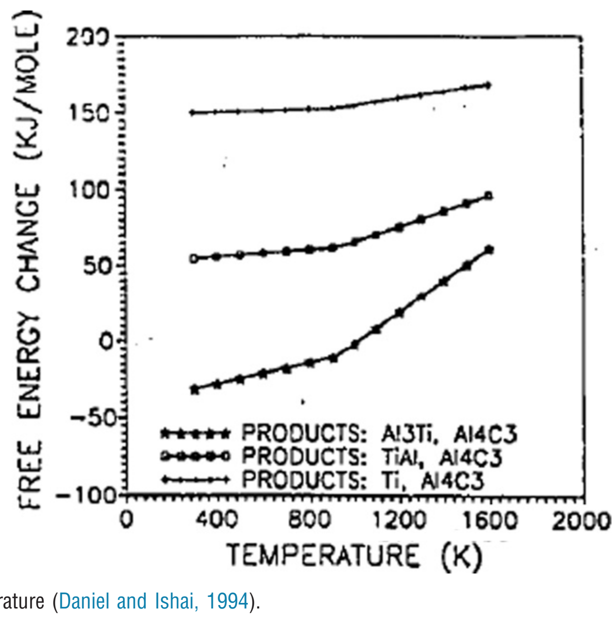

Figure 1 The free energy vs. temperature (Daniel and Ishai, 1994).

4.4 Particulate Reinforcement

The improvement in toughness due to the particulate reinforcement depends on the residual stresses surrounding the particles, the weight fraction of the particles, size and shape of the particles (Huda *et al.*, 1993; Suery and Esperance, 1993). Particles can be spherical, disk-shaped, rod shaped, and plate shaped. Each particle forces the crack to go out of plane, and can force the crack to deflect in more than one direction and thus increase the fracture surface energy (Gogopsi, 1994). Plate and rod shaped particles can increase the composite toughness by another mechanism called as 'pullout' and 'bridging'. The residual stress around the particles results from thermal expansion mismatch between the particles and the matrix, which helps to resist the crack propagation. The term 'particulates' is used to distinguish these materials from particle and referred as a large, diverge group of materials that consists of minute particles. The second phase particle can produce small but significant increase in toughness and consequently increases its strength through crack deflection processes. The particles, sometimes given a proprietary coating can be used for improving strength. When compared to whiskers-reinforcement systems, particle reinforcement systems have less processing difficulties and should permit to add higher weight fractions of the reinforcing phase. The orientation of particles appears as flat plates (Matthew and Rawlings, 1999; Pardo *et al.*, 2005).

Reinforcements for metal matrix composites have a manifold demand profile, which is determined by production and processing and by the matrix system of the composite material. The following demands are generally applicable (Hashim *et al.*, 1999; Kainer, 2006):

i. Low density
ii. Mechanical compatibility (a thermal expansion coefficient which is low but adapted to the matrix)
iii. Chemical compatibility
iv. Thermal stability
v. High Young's modulus
vi. High compression and tensile strength
vii. Good processability and
viii. Economic efficienncy.

5 Properties of Composites Relevant to Aluminum-Based MMCs

Aluminum is the most popular matrix for the metal matrix composites (MMCs). The aluminum alloys are quite attractive due to their low density, their good corrosion resistance, their capability to be strengthened by precipitation, their high vibration damping capacity and high thermal and electrical conductivity (Sayuti *et al.*, 2011a,b,c,d,e; Suraya *et al.*, 2011). Aluminum matrix composites have been used since the 1920s and are now used in electronic packaging, sporting goods, armors and automotive industries. They offer a large variety of mechanical properties depending on the chemical composition of the aluminum matrix. They are usually reinforced by aluminum oxide, silicon dioxide, silicon carbide, carbon, boron nitride, graphite, boron, boron carbide etc. and aluminum nitride is also dispersed in the matrix. In the 1980s, transportation industries began to develop discontinuously reinforced aluminum matrix composites. They are very attractive for their isotropic mechanical properties and their low costs. The properties of composites of MMCs are inevitably a compromise between the properties of the matrix and reinforcement phases (Doel and Bowen, 1996). It is clear that the composition and properties of the matrix phase affect the properties of the composite both directly, by normal strengthening mechanisms, and indirectly, by chemical interactions at the reinforcement/matrix interface (Kalpakjian, 1995). Aluminum based composites, reinforced with ceramic particles, offer improvements over the matrix alloy: an elastic modulus higher than that of aluminum has a value of 70 GPa, a coefficient of thermal expansion which is closer to that of steel or of cast iron, a greater resistance to wear and an improvement in rupture stress especially at higher temperatures and possibly improved resistance to thermal fatigue (Ejiofor and Reddy, 1997). In addition to the benefits listed above, there are decreases in elongation to failure and fracture toughness. Fortunately, the introduction of aluminum–silicon/ceramic composites seems to provide a good basis for manufacturing pistons which may be expected to meet the demands to withstand higher cylinder pressures, increased fuel injection rates and higher operating temperatures. Increasing the weight fraction percentage of silicon carbide particulates addition in the LM6 alloy matrix has increased ultimate tensile stresses, modulus, yield but a reduced strain to fracture (Chawla and Shen, 2001). However, it is seen that that silicon content of the matrix has a dominant effect in reducing the fracture strain more than the increase in silicon carbide particulate addition.

The strength of particulate MMCs has been addressed by both a continuum mechanics, based upon shear-lag-type models, Eshelby's equivalent inclusion technique, finite elements methods and a dislocation mechanics approach. However, the aluminum–12% silicon materials have relatively higher fatigue strength compared with those contained 5% silicon. Endurance limit based on 10^7 cycles decreases with silicon carbide addition in the LM6 alloy–silicon carbide particulate composites. In the case of sillimanite particulate reinforced aluminum matrix composites, the hardness of the matrix alloy has increased from 57 to 85 HV due to the dispersion of the sillimanite particles in the matrix. This may be attributed to the significantly higher hardness value, 650 HV of the sillimanite particles, and the matrix becomes plastically constrained due to thermal residual stress in the presence of the sillimanite particles (Singh *et al.*, 2001). Many of the properties of particulate reinforced metal matrix composites like strength, ductility, stiffness, etc. fall below the predicted values by the rule of mixtures. For 10% weight fraction addition of sillimanite particles in the aluminum–silicon alloy, the ultimate tensile strength has decreased marginally from 132 to 121 MPa and percentage elongation has decreased significantly from 2.25 to 1.42%. Same properties results are found and similar to those of other aluminum–silicon alloy composites dispersed with other hard particles. This is primarily due to the mechanical type of bonding and ineffective load transfer from the matrix to the reinforcement (Dai *et al.*, 2001).

Boron-reinforced aluminum MMC combines the outstanding strength, low density and stiffness of the boron fiber with fabrication and engineering reliability of an aluminum alloy. The overall improvement in modulus to density ratio of the boron fiber is almost six times that of any of the standard engineering materials, including steel, molybdenum, aluminum and magnesium. This is advantageous in the prevention of micro buckling of fibers in the matrix under compression. Other important physical and mechanical properties of boron/aluminum composites include ductility, high electrical and thermal conductivity, toughness, non-flammability and ability to be coated, formable and joinable through heat treatment (Hu and Yan, 2011).

The graphite/aluminum composites are very attractive because the composite can be designed with the coefficient of thermal expansion approaching zero. The extremely high stiffness of the graphite fibers makes possible a composite that is ideal for applications where precise pointing and tracking are required. These are well suited for start strut assemblies, especially in space structures that are subject to a wide range of temperature across them. Graphite/aluminum is also applicable for stable instrument platforms, electronics, and thermal control devices such as heat pipes. Stiffness to weight ratio is high since the material is 30 percent stiffer than aluminum with no thermal expansion. Dispersion of graphite particles in aluminum–silicon alloy provides the alloy with antifriction properties, good wear properties such as wear rate, P–V limits, seizure resistance, high damping characteristics, and good machinability. As a result, most developmental activities on this class of composites have focused more on their microstructure and tribological characteristics than on mechanical properties (Vijayaram, 2006; Sayuti *et al.*, 2011a,b,c,d,e; Taufik *et al.*, 2011d).

The alumina dispersoid is thermodynamically stable in molten aluminum alloy containing no magnesium. As a result, wetting and bonding is achieved by changing the surface chemistry of the dispersoids or by alloy additions such as magnesium and nickel to the matrix melt. Additions of 3% weight fraction of alumina having a size of 100 µm to the aluminum alloy matrix has increased the hardness from 27BHN to 37BHN and the ultimate tensile strength from 75 to 93 MPa, it reduced the ultimate tensile strength of aluminum–8% silicon alloy from 157 to 123 MPa. Zircon, which is relatively heavier than many ceramic particles, requires little or no vortex before introduction into the alloy melt. Hardness and abrasive wear resistance, ultimate tensile strength, and yield strength are increased with the amount of zircon addition in the aluminum matrix while the percentage of elongation is decreased (Warren and Hunt, 2000).

Fly ash reinforced aluminum alloy matrix composites processed by casting vortex-mixing process showed better abrasion resistance and wear resistance than the monolithic aluminum and aluminum alloys. Specific abrasive wear rate of aluminum alloy with 3% weight fraction of fly ash is decreased with increasing load and increasing sliding velocity. The aluminum–alloy with 3% weight fraction of fly ash showed better resistance than the base alloy up to 24 N. Specific abrasive wear rates of the composite containing 3% fly ash decreased with the decreasing size of the abraded particles. Friction coefficients of the fly ash composites decreased with increasing time, load and size of the abrading particles. Fly ash alloy aluminum composites are significantly lighter when compared to steel (Jamasri *et al.*, 2010).

5.1 Material Selected for Processing Composites

Materials used in this research project are aluminum–11.8% silicon alloy, and titanium carbide particulate. They are added in different percentages on weight fraction basis and hence to produce different types of particulate reinforced metal matrix composites. Mechanical vibration moulding is used during solidification of cast-composites. The economics of the composite slurry casting process is strongly influenced by the viscosity of the molten matrix (Mortensen *et al.*, 1989). Sand mould are used to pour the composite slurry mixture in the slab shape molded cavities to make the composite castings.

5.1.1 Aluminum–11.8% silicon eutectic alloy

The matrix material used in this research work is aluminum–silicon alloy (Metals Handbook, ASM, 1973). It is based on British specifications that conforms to BS 1490–1988 as Aluminum–11.8% silicon alloy. It is actually a eutectic alloy having the lowest melting point that can be seen from the Aluminum–Silicon phase diagram. Aluminum–11.8% silicon alloy is corrosion resistant with average durability and strength, and possess high impact strength and ductility (Hells and Brandes, 1976; Pio, 2005). The chemical composition of the melted alloy is analyzed by a spectrometer and the various constituents present is shown in **Table 8** (Woodward, 1989).

The chemical composition of aluminum–11.8% silicon alloy is about 85.95% of aluminum, 11–13% of silicon. The mechanical, thermal and electrical property of aluminum–11.8% silicon alloy is shown in **Table 9** (Kaye and Laby, 1996).

The common composite material candidates are aluminum, lithium, magnesium, magnesium and titanium alloy composites. They are processed as different component parts aimed from improving the limited properties of conventional aluminum

Table 8 Composition of Aluminum–11.8% silicon alloy expressed in percentage

Al	*Cu*	*Mg*	*Si*	*Fe*	*Mn*	*Ni*	*Zn*	*Lead*	*Tin*	*Titanium*	*Others*
85.95	0.2	0.1	11.8	0.5	0.5	0.1	0.1	0.1	0.05	0.2	0.2

Source: Woodward, 1989.

Table 9 Mechanical, thermal and electrical properties of Aluminum–11.8% silicon alloy

	Values
Physical properties	
Density (gm cc^{-1})	2.66
Mechanical properties	
Tensile strength, ultimate (MPa)	290
Tensile strength, yield (MPa)	131
%Elongation break (%)	3.5
Poisson's ratio	0.33
Fatigue strength (MPa)	130
Machinability	30
Shear strength (MPa)	170
Hardness (BHN)	50
Modulus of elasticity, E (N mm^{-2})	71 000
Thermal properties	
CTE, linear 20 °C (μm m^{-1} °C^{-1})	20.4
CTE, linear 250 °C (μm m^{-1} °C^{-1})	22.4
Heat capacity (J g^{-1} °C^{-1})	0.963
Heat of fusion (J g^{-1})	389
Thermal conductivity (W m^{-1} K^{-1})	155
Melting point (°C)	574
Solidus (°C)	574
Liquidus (°C)	582
Electrical properties	
Electrical resistivity (Ω cm^{-1})	0.000 004 4

Source: Kaye and Laby, 1996.

properties like weight reduction, elevated temperature for engine components and highly loaded engines, wear resistance for brake disks, drums, and cylinder blocks and modulus of elasticity for calipers (Ejiofor and Reddy, 1997).

5.1.2 Titanium carbide

Titanium carbide is a ceramic material normally used for aerospace applications. The molecular weight of titanium carbide is 59.89, its melting point is 3140 °C, and boiling point is 4820 °C. The density of tungsten carbide is 4.93 gm cc^{-1} and Mohs hardness at 20 °C is 3200 kg m^{-2}. The crystal structure of tungsten carbide is of cubic type. The electrical resistivity of titanium carbide ranges from 180 to 250 μΩ cm (Neeley and Bertone, 2000).

6 Vibrations

In general, vibration is the motion of the particles of an elastic body or medium in alternately opposite direction of equilibrium, periodically in time. Pillai *et al.* (2004) have published an extensive survey of different techniques of vibration used during solidification and their effect on the final structure.

6.1 Ultrasonic Vibrations

Eskin (1994) summarized the effect of ultrasonic vibration treatment on light alloy materials. Work of various researchers demonstrated that ultrasonic vibrations method can be used for cavitations, fine filtration of melts (the USFIRALS process), melt degassing, spatial solidification, non-dendritic solidification, improved semi-solid deformation and for the production of aluminum alloys with low-solubility component (Eskin and Eskin, 2003). The ultrasonic treatment is an effective method for degassing aluminum melts (Xinbao *et al.*, 2008; Xu *et al.*, 2004). Also the ultrasonic vibrations could be used to refine eutectic silicon in hypoeutectic Al–Si alloys (Jian *et al.*, 2006). **Figure 2** shows the effect of ultrasonic vibrations on the morphology of eutectic Si (Jian *et al.*, 2006) and **Figure 3** shows the effect of ultrasonic vibration on the grain structure of A356 alloy (Jian *et al.*, 2005).

Although ultrasonic vibrations technique have shown favorable effects on the solidification characteristics of aluminum alloy, its commercial applications are constrained mainly because of the difficulties to use of ultrasonic instruments on the foundry floor (Jian *et al.*, 2005).

Gao *et al.* (2009) investigated the effects of ultrasonic vibration on solidification process of AZ91 alloy with different powers from 0 to 700 W. Without subject to ultrasonic vibration (0 W of ultrasonic power), the dendrites were coarse and large. Globular grains were obtained in AZ91 alloy subjected to high intensity ultrasonic vibration. The grain size of AZ91 was decreased gradually from 202 to 146 μm with increasing ultrasonic vibration power. The ultimate tensile strength was increased from 145 to 195 MPa and elongation to fracture from 2.3 to 5.2% correspondingly with increasing ultrasonic vibration power.

Hiedemann (1954) studied three different techniques to induce mechanical vibration such as mechanical vibrator, electromechanical transducers and electrodynamical excitation. The researcher found that sonic and ultrasonic treatment has a clear effect on variety of metallurgical properties such as reduction of degassing of melts, grain size and dispersion of substances in melts. Summary of the influence of vibration is listed in **Table 10**.

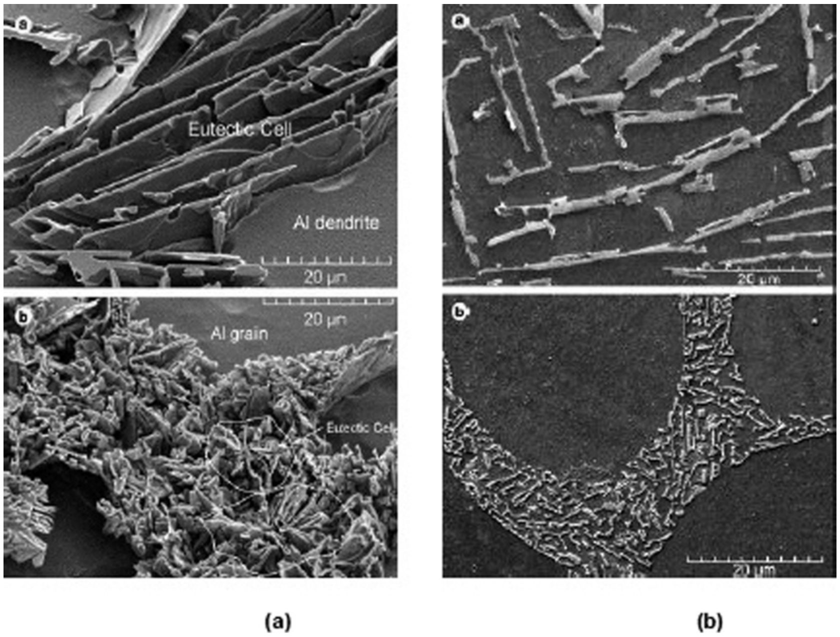

Figure 2 Eutectic Si Morphology (a) without ultrasonic vibration and (b) with ultrasonic vibration (Jian *et al.*, 2006).

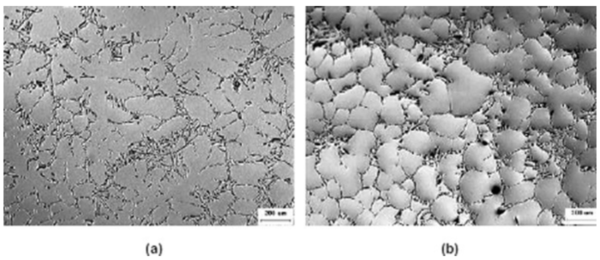

Figure 3 Effect of ultrasonic vibrations on microstructure of A356 alloy, without ultrasonic vibration (a) and (b) with ultrasonic vibrations (Jian *et al.*, 2005).

Table 10 Summary of the effect of vibration on metallurgical properties of materials

Alloy	*Vibration condition*	*Metallurgical properties*	*Mechanical properties*	*Other remark*
Sn–Zn eutectic	Sonic	Finer zinc needles	–	–
Sn, Zn and Al	600–4500 kHz	Dendritic structure	–	–
Fe–zinc	9 kHz	Increased Fe solution in Zn	–	–
Sb, Cd, Silumin, Duralumin	10 kHz	Smaller grain size	Increase hardness, Sb 52%, Duralmin 23%	Reduced brittleness of Sn
Mg–45AlMg–12%Al	50 Hz, 280 kHz	True eutectic instead of irregular structure.	–	50 Hz give more refinement
Wood's alloys	50 Hz, 9 kHz, 284 kHz (1.4 W cm^{-2})	Shortening of needles	–	More efficient with high intensity

Source: Hiedemann, 1954.

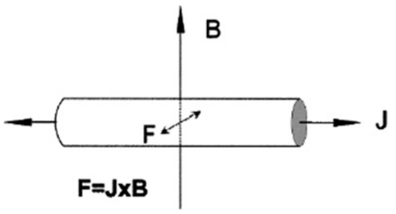

Figure 4 Force vibration direction F developed by the alternating electric field J and the stationary magnetic field B interaction (Alireza and Miwa, 2000).

6.2 Electro-Magnetic Vibrations

As the name suggests, electromagnetic vibrations typically involve two different force fields, namely an alternating electric field and a stationary magnetic field. If a stationary magnetic field with a magnetic flux density 'B' and an alternating electrical field with a frequency 'f' and current density 'J' is applied to a melt, then an electromagnetic vibrating body force with a density 'F' is induced inside the melt, where $F=J \times B$. This force 'F' sets the particles inside the melt into vibration motion with a frequency equal to the frequency of the alternating electrical field, and the particlesvibrating perpendicular to the plane of vector J and B (Alireza and Miwa, 2000). An effect of this electromagnetic force is formed inside the melt due to the applied magnetic force and the induced force. This force is partly rotational and stirs the melt. **Figure 4** illustrates the relationship between these forces.

Applied low frequency electromagnetic vibration could be used to grain refinement, to avoid cracks, to eliminate micro segregation and improve the as-cast surface quality of alloys. Pak *et al.* (2005, 2007) studied that electromagnetic vibrations reduced the grain size of primary silicon. They attributed this phenomenon to the collision of primary Si particles with one another. Yoshiki *et al.* (2004) imposed electromagnetic vibrations on an Al–7 wt% Si alloy and found that with an increasing frequency of the vibrations, the primary a-Al dendrites approached a globular shape of about 25 μm in size. Mizutani *et al.* (2006) also found that in Al–17 wt% Si, the primary Si particles were refined to 5 μm at a frequency nearing 1 kHz. The level of grain refinement increases with the frequency of vibration. They attributed this phenomenon to collapsed dendrite arms due to micro-explosion and stirring that took place in the melt. Various researchers including Hernández and Sokolowski (2005) and Vives (1996) reported that electromagnetic vibrations can improve the surface quality of the castings, refined primary and eutectic Si, refined and uniform grain structure.

6.3 Mechanical Vibration

In this technique, the molding is set into vibration by means of a vibration source that is mechanically operated. Although the use of mechanical vibrations allows limited degrees of freedom to the operator, it is the most promising technique of applying vibrations to solidifying melts. This technique is very simple and a rugged equipment that is needed for inducing vibrations.

Vibrations: A periodic motion of the particles of an elastic body or medium in alternately opposite directions from the equilibrium position when that equilibrium is disturbed.

Amplitude: The severity of vibration.

- Peak-to-peak
- Zero-to-zero

- Average value
- Root means square value

For the purposes of this work, all values of amplitude are represented in the form of Root Mean Square Value (RMS).
Frequency: The number of cycles that a system will perform in a unit time. It is usually measured in Hertz (Hz).

6.4 Mechanical Vibrations Moulding in Casting

Campbell (1981) reported that the mechanical vibration during solidification causes improvement in mechanical, physical and corrosion properties of alloys. Mechanical vibrations have also been linked to the reduction of complete removal of the tendency for pipe formation in ingots of pure metals (Fisher, 1973). **Figure 5** shows fragmentation of the dendrites caused by applied mechanical vibration moulding during solidification of NH_4CL-H_20.

Bast *et al.* (2004) reported that the effect of mechanical vibrations on pure Aluminum, Al 12 wt%Si alloys and Al7 wt%SiMg along with other non-ferrous alloys. Their research focused on the influence of mechanical vibrations on grain refinement and mechanical properties. They observed that the cooling rate and the degree of grain refinement improve with the frequency of vibrations and the grain size becomes more homogenous. The influence of mechanical vibrations on the solidification behavior of pure Aluminum is shown in **Figure 6**. The dependence of the castings wall thickness on casting characteristic could be minimized with the use of mechanical vibrations during solidification.

Pillai *et al.* (2004) used vibration during solidification with low frequency (100 and 200 cycles min^{-1}) to study its influence on A356 and Al–12Si alloy. They summarized that mechanical vibrations can increase the Ultimate Tensile Strength (UTS), hardness, elongation, and density of the cast materials. They attributed these improvements to the increased coagulation of hydrogen bubbles and their escape from the melt brought about by the vibration of the molding. Thus, porosity was decreased and wetting of the mould walls by the melt was improved, this in turn promoted faster heat transfer and fragmentation of the solid formed on the mould wall (Kocatepe, 2007). However, the technique used by Pillai *et al.* (2004) for generating the low frequency vibrating (mould tilting and hand tapping) is highly impractical in a production foundry environment. The vibrations of 15–41.7 Hz

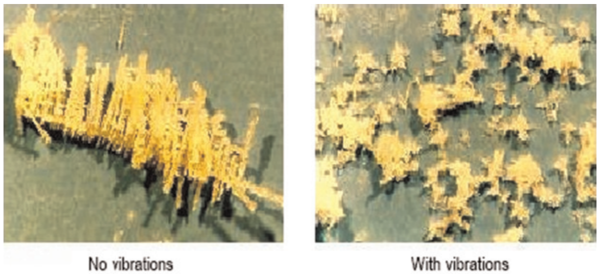

Figure 5 Fragmentation of Dendrite while solidification of NH_4CL–H_2O with vibrations (Numan *et al.*, 2005).

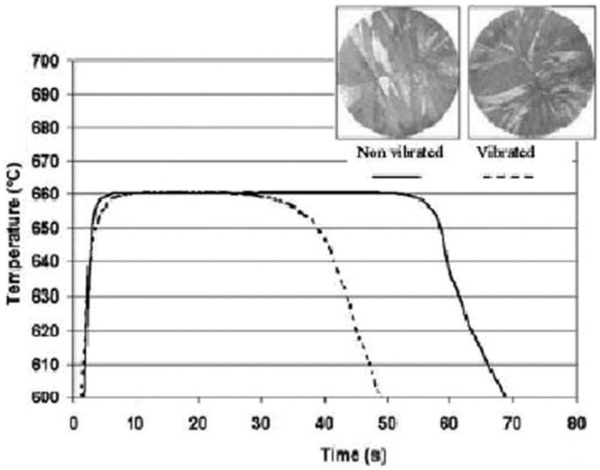

Figure 6 Influence of mechanical vibrations on the cooling curve of pure aluminum (Bast *et al.*, 2004).

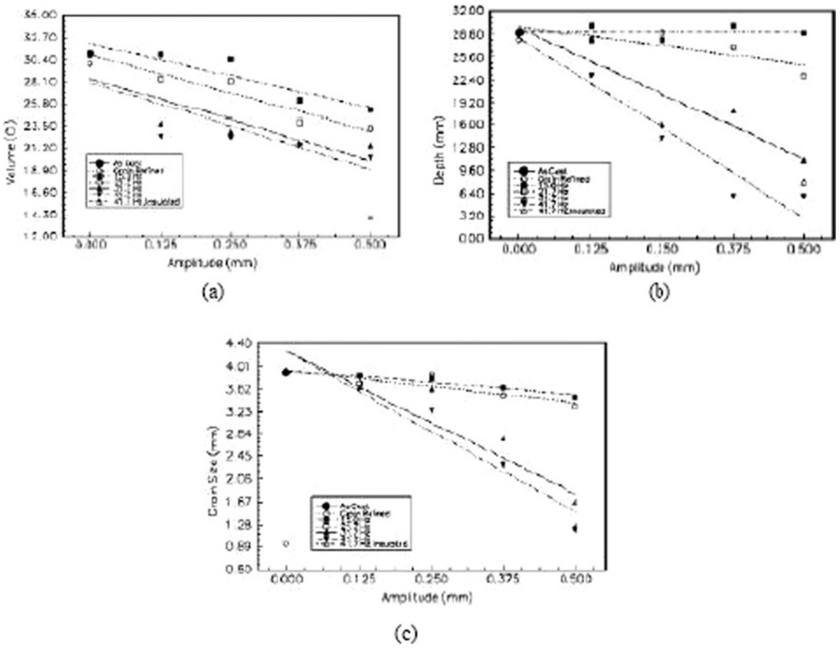

Figure 7 Influence of mechanical vibrations on (a) pipe volume, (b) pipe depth and (c) grain size of Al–12.3Si Ingot casting (Kocatepe and Burdett, 2000).

frequency and 0.125–0.5 mm amplitude to Al–12.3Si alloy ingots poured in a graphite mould has been applied by Kocatepe and Burdett (2000). They found that at 41.7 Hz, the solidification time of the casting was decreased by 24%, pipe volume was decreased by 55% and grain size was decreased by 52% as compared to the casting prepared without vibration as shown in **Figure 7**.

But Kocatepe (2007) and Kocatepe and Burdett (2000) have studied that the mechanical vibrations caused coarsening of the eutectic silicon due to an increase in diffusivity of silicon in the liquid caused by the effect of vibrations. They attributed the observed grain refinement to mainly the fragmentation of dendrites and growing crystallites during the early stages of solidification.

Numan *et al.* (2005) used an electromagnetic shaker to induce mechanical vibrations in a die molding. They vibrated the die moulding at frequencies ranging from 100 Hz to 2 kHz and amplitudes ranging from 3.73 to 199 μm and recorded the thermal history at different points in the moulding. Their studies on AA356 alloy reveals that vibration homogenizes the temperature distribution in the mould and promotes a faster cooling rate. This manifested itself in more uniform dendrite structure and decreased porosity in the castings. They observed fragmentation of the dendritic structure in Al12.5%Si. They found that the degree of fragmentation increased with the amplitude of vibration. They also reported that the eutectic structure transformed from the typical flaky structure to a more fibrous structure with increasing amplitude of vibration up to 149 μm as shown in **Figure 8**. Beyond 149 μm, the fibrous eutectic silicon agglomerated to form a structure of coarse flakes. Numan *et al.* (2005) also reported that certain mechanical properties were affected by the application of vibration. They found that there was an increase in % elongation from 19 to 68% and a slight increase in UTS by 3%.

Chirita *et al.* (2009) reported that the influence of mechanical mould vibration during solidification on the mechanical properties of Al–Si hypereutectic alloy castings with different frequencies. The main influence of vibration include promotion of nucleation, reduction of shrinkage porosities due to improved metal feeding and reducing as-cast grain size and production of a more homogenous metal structure. The results show that the mechanical properties were influenced by the level of applied frequency. The tensile strength properties were improved for low vibration frequencies but the tensile strength decreased for high frequencies, as compared with gravity castings without vibration.

7 Research Methodology

In this research project, experimental work has been carried out to determine the mechanical properties, physical properties, thermal conductivity, thermal diffusivity and fracture surface condition of the specimens after tensile testing. The first section explains the selected composite fabrication process of the samples in the form of plates. The second section deals with the experimental work done throughout the study. The flow chart for the overall study is shown in **Figure 9** which also illustrates the

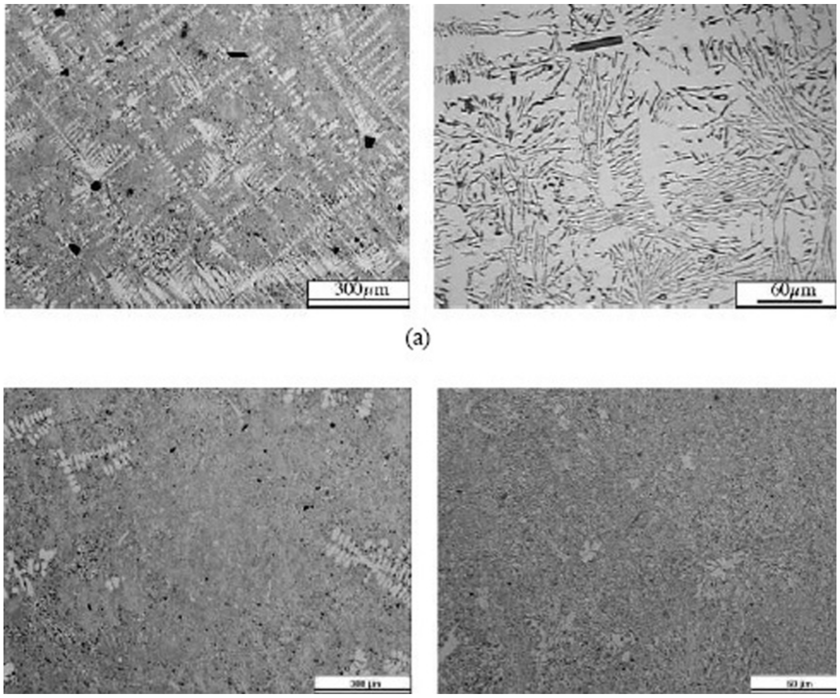

Figure 8 Morphology of Eutectic Silicon (a) without vibrations (b) with vibration at a frequency 100 Hz and an amplitude of 149 μm (Numan *et al.*, 2005).

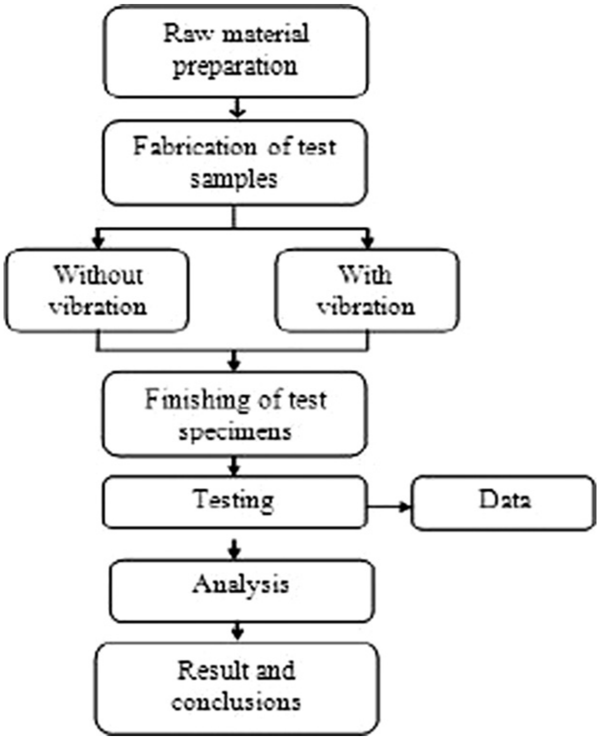

Figure 9 Flow chart of the plan to carry out the work.

outline of the investigation. The experimental work was divided into two parts. The first part is the composite plate fabrication process and it is shown in the flow chart in **Figure 10**. The experimental testing is in the second part of the study. The tensile tests, hardness test and impact tests were performed to determine the mechanical properties whilst scanning electron microscope was used to identify and characterize the morphological features of the composites.

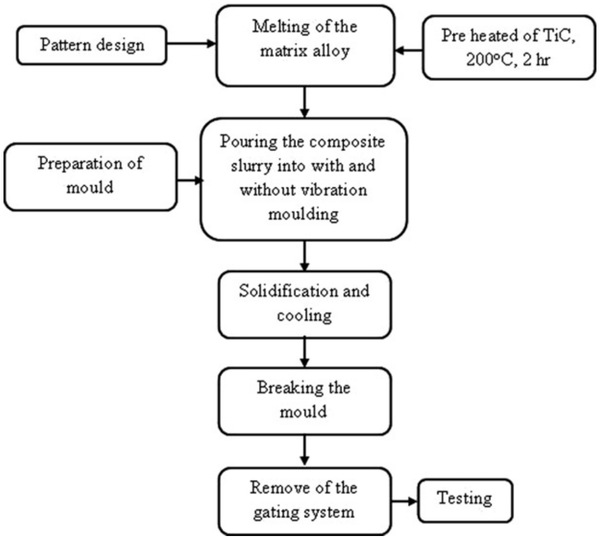

Figure 10 Flow chart of the composite fabrication process.

7.1 Preparation of Specimens

The most common tests performed on composite material are designed to determine the tensile properties.Tensile specimens are made to conduct the test. Because most composites have a high ratio tensile strength to shear strength, the 'tab' area of dog bone geometry tends to shear off.If a straight-sided specimen is used, stress concentrations from gripping cause failure. Therefore, many composite specimens require doublers tabs to be bonded to both sides at the ends. The tabs distribute gripping stresses and prevent specimen failure caused by grip jaws damaging the specimen's surface.Processed tensile test specimens of TiC particulate reinforced LM6 alloy composites are prepared according to ASTM standards B 557M-94.

7.2 Production Methods of Metal Matrix Composite Materials

The following section explains the production methods of metal matrix composite materials:

a) Composite materials with a metal matrix are produced by casting technology and powder metallurgical technique. In the casting method, the liquid matrix material is reinforced by a particulate.
b) A mixture of particulates and discontinuous fibers are also reinforced with a matrix to produce composites.
c) In this project, mechanical vibration mould method was used during solidification to produce slab of composites casting.

7.2.1 Particulate reinforced metal matrix composite casting fabrication by mechanical vibration

In this project work, titanium carbide as particulate are added in the alloy matrix by varying the weight fraction % addition and various frequency to the aluminum–11.8% silicon alloy matrix to process four types of particulate reinforced composite castings. The weight fraction percentage addition of each type of particulate to the alloy matrix varies from one type of particulate to another particulate and priorly a few calculations are required to determine the weight fraction % to be added to the selected alloy matrix material. As explained for every type of reinforcement phase, a separate calculation is performed and it is explained in the consecutive section.

7.2.2 Characterization of particulates selected for this research work

The particulates are branded under Fluka and Aldrich. The product name itself is defined as 'Titanium (IV) carbide' and specifications like chemical composition and size in micron are identified in the label of the container box. Since it is a standardized report from Fluka, X-ray diffraction analysis is not required and hence not performed in this project. Similarly, all the details of characterization on other particulates are available from the supplier's catalog. Titanium carbide particulate reinforced metal matrix composites are fabricated by casting technique (Kennedy and Wyatt, 2001). The selected matrix material is aluminum–11.8% silicon alloy. The net weight of the designed composite slab casting is equal to 302.10 g. In this study, 0.2, 0.6, 1 and 2% of titanium carbide is added to the melt and these particular weight fraction percentages were selected purely arbitrarily.

7.2.3 Melting and casting of particulate reinforced metal matrix composites

In this research project, an induction furnace is used to melt the aluminum–11.8% silicon matrix alloy. This furnace is a core less type and does not have a core inside. It has a crucible surrounded by water-cooled coil, which produces the magnetic field and eddy current. The metal charge acts as the secondary coil and stirring action takes place to mix the alloy constituents. Under capacity of 65 tons, the furnace controls the temperature and composition of the metal well. A ladle is used to transfer the molten metal from furnace to the crucible. The main concern is to maintain the temperature while transferring the molten metal to the crucible and hence to ensure the quality of the cast product. The metal handling equipment is used to transfer the molten metal and it depends on the mold size and the quality of cast being cast.

7.2.4 Preparation of particulate samples and preheating procedure

The particulates are weighed by a digital electronic balance and it is transferred in a metal cup. Then, it is kept inside a muffle furnace and the preheating temperature is selected and hence to maintain the same for a period. The muffle furnace is similar to a heat treatment furnace and the temperature can be raised up to 1000 °C. For the particulates used in this project, 200 °C is chosen and maintained for 2 h without disturbing it (Vijayaram, 2009). After the set time, slowly the furnace is opened and the preheated particulate is immediately transferred to the crucible and the vortex mixing process is continued without delaying. From the literature, it is noted that the wettability between the particulate surface and the alloy matrix will be satisfactory only if it is transferred at a faster rate leading to the impeller blade mixing. The purpose of heating the particulate is to remove the volatiles present on it and hence to create thermoelectric charges on it. Due to this, the wettability is improved and bonding is formed between them. Due to the repulsive action of the same thermoelectric charges on the surface of the heated particulates, uniform particulate distribution is attained in the composite castings.

7.3 Testing

Two categories of tests are significant for this research project, among them; one is the properties testing such as mechanical properties, physical properties and thermal properties. These specimens are tested using the Instron 8500 universal testing machine, manufactured by Tec equipment Ltd., England, UK.

Next is the metallographic analysis with the aid of a metallurgical microscope to study the particulate distribution uniformity and hence to characterize the phases present in the processed composites. Tensile tests are carried out by using an Instron universal testing machine to determine the tensile properties of the material such as tensile strength, yield stress, fracture stress, Young's modulus, percentage of elongation, ductility and other allied properties. At least five samples were tested for each of the category of composite produced and the mean values taken (Aji *et al.*, 2011; Chirita *et al.*, 2009; Ozden *et al.*, 2007).

7.3.1 Tensile testing

This test is conducted to determine the mechanical properties of the processed titanium carbide particulate reinforced aluminum–11.8% silicon alloy matrix composites. Tensile test specimens are made according to the BS standards and specifications.

Titanium carbide particulate reinforced aluminum–11.8% silicon alloy matrix composite tensile testing specimens are made from the composite slab castings processed by sand mold casting technique. Different weight fraction % of titanium carbide particulates are added to produce the composite slab castings to make the test samples for tensile testing. The test samples are subjected to a tensile load and the mechanical properties are determined. Hence, the tensile strength, Young's modulus values are calculated. For the tensile test, INSTRON 8500 machine is used and a tensile load is applied within 20 kN in this particular testing process.

7.3.2 Hardness test

Hardness values of different vibration frequency of the processed composites are determined for different weight fraction % of titanium carbide particulate containing aluminum–11.8% silicon alloy and graphs are plotted between the hardness value and the corresponding type of particulate addition on weight fraction basis (Levita *et al.*, 1990). The hardness of composites is tested by MITUTOYO ATK-600 MODEL hardness testing machine.

7.3.3 Impact test

Impact strength of particulate composites is determined for every type of particulate reinforcement by conducting the impact testing on the standard impact samples, at least three numbers (Noble, 1996). In this project, impact charpy values are determined from the reading taken in an impact-testing machine: Gunt tester available in the UPM strength of materials laboratory of the Mechanical and Manufacturing Engineering department.

7.3.4 Metallograpy (optical metallurgical microscopy)

Metallurgical microscope is employed to study the microstructures of the test samples at different magnifications made from the processed composite slab castings (Sayuti *et al.*, 2012a,b,c). Hence, photomicrographs are developed and it helps to determine the particulate distribution in the matrix, interfacial adhesion between particulate and matrix, and to identify the presence of micro defects.

7.3.5 Scanning Electron Microscopy

Scanning Electron Microscopy (SEM) is an important tool to characterize a wide range of materials from pure metals to advanced materials like composites, nanostructured materials, and super alloys and so on. The unique advantage of this technique is that the interior details of the processed materials like the crystallographic structures, dislocation of the planes, intermetallic phases and precipitates, microstructures and defective locations can be identified very easily at higher magnifications and resolution (Avner, 1987).

7.3.6 Density measurement

The density of a material is defined as its mass per unit volume. A&D-GR 200 – Analytical Balance was used to conduct the density measurement. The theoretical density of each set of composites was calculated using the rule of mixtures (Rizkalla and Abdulwahed, 1996). Each pellet was weighed in air (Wa), then suspended in Xylene and weighed again (W). The density of the pellet was calculated according to the formula (Rizkalla and Abdulwahed, 1996; Taghavi *et al.*, 2009):

$$Density = \frac{Wa}{(Wa - Ww)} \times density\ of\ Xylene \qquad [7]$$

7.3.7 Thermal properties

Thermal diffusivity of composite materials is measured using photo flash method. The photoflash detection system consists of a light source, sample holder, thermocouple, low noise pre amplifier, oscilloscope, photodiode and a personal computer. The temperature rise at the back surface of the sample is detected by the thermocouple. The detected signal is amplified by a low-noise preamplifier and the processed by a digital oscilloscope (Carter and Norton, 2007; Yu *et al.*, 2002).

Photoflash detection system is not an expensive method and the standard thermal diffusivity value for aluminum is equal to 0.83 $cm^2\ s^{-1}$ for thickness greater than 0.366 cm (Muta *et al.*, 2003). In the photo flash system, the excitation source consists of a high intensity camera flash. This method is well suitable for aluminum, aluminum alloys and aluminum–silicon particulate metal matrix composites (Collieu and Powney, 1973). The thermal diffusivity values can be obtained for different thicknesses of the test samples. The thermal diffusivity, α determines the speed of propagation of heat waves by conduction during changes of temperature with time. It can be related to α, the thermal conductivity through the following equation (Michot *et al.*, 2008; Taylor, 1980).

$$K = \alpha\ (\rho \mathrm{Cp}) \qquad [8]$$

where density ρ and specific heat Cp.

The photo flash technique is originally described by Parker and it is one of the most common ways to measure the thermal diffusivity of the solid samples. The computer is programmed to calculate the thermal diffusivity, α, using the equation:

$$\alpha = \frac{(1.37xL^2)}{\left[(3.14)^2 xt_{0.5}\right]} \qquad [9]$$

where L is the thickness in mm and $t_{0.5}$ is the half rise time in seconds.

8 Result and Discussion

8.1 Mechanical Properties

The impact properties of particulate reinforced aluminum alloy matrix composite with and without vibration composite are given in **Figure 11**. The mechanical properties of the composite with vibration are always better than that of correspondent without vibration. As shown in the figure, the impact energy value increases with increase in percent weight fraction of TiC and with using vibration during solidification. Mechanical vibration makes solidification microstructure of aluminum matrix composite fine and homogeneous and decrease the amount of defect such as shrinkage cavity and inclusions. The effect of vibration to help in the promotion of nucleation and thus reducing as-cat grain size, reducing hydrogen, reducing shrinkage porosities due to improved metal feeding, and producing a more homogenous composites structure (Chirita *et al.*, 2009; Kocatepe and Burdett, 2000; Xu *et al.*, 2008). These improved features lead to improve mechanical properties and lower susceptibility to cracking. Literature review on the effects of vibration on casting and reported an improvement of mechanical properties by as much as 40% (Campbell, 1981). It can be concluded that these effects play an important role on the improvement of impact energy. **Figure 12** offer the comparison of the mechanical vibration effect and weight fraction of the particles effect on the density. It is easy to draw a conclusion that, by mechanical vibration during solidification, the size of shrinkage cavity and inclusion are reduced and the amount of defects is also decreased. The densities of the samples are measured using A&D-GR 200 – Analytical Balance. It can be found that the density is higher in the sample with mechanical vibration mould than in without vibration mould. It is obvious that the amount of defect

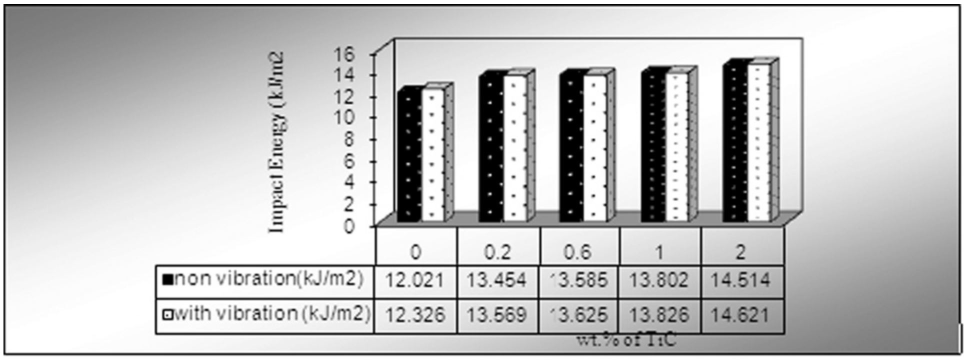

Figure 11 Average of Impact energy vs. wt% of TiC.

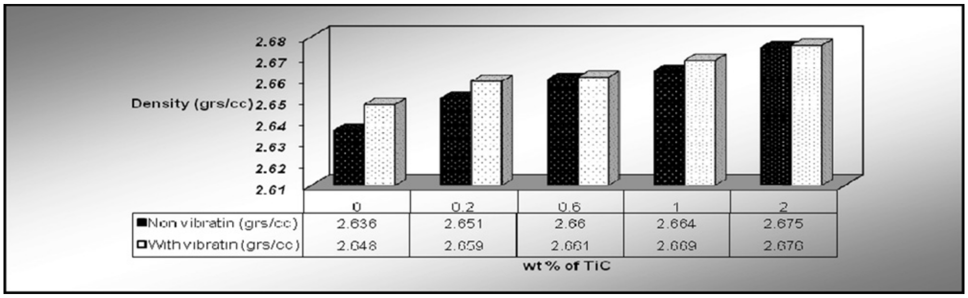

Figure 12 Average of density energy vs. wt% of TiC.

Table 11 Mechanical properties of TiC particulates

wt% of TiC	*Tensile strength (MPa)*		*Young's modulus (MPa)*		*Hardness*	
	Non vib.	*With vib.*	*Non vib.*	*With vib.*	*Non vib.*	*With vib.*
0	116.0743	118.6800	1638.3156	1762.2564	79.91	80.72
0.2	123.9025	126.6624	1881.2463	1909.2886	81.06	81.20
0.6	130.9343	133.3083	1972.1417	1974.8320	81.32	82.04
1	133.9486	134.0294	1990.3139	1990.5429	83.90	84.86
2	135.8325	135.8454	1998.4230	1998.5130	85.88	85.96

such as shrinkage cavity and inclusion is decreased and the compactness is enhanced due to applied mechanical vibration during the solidification process. The values of density in composites also increase with increasing weight fraction of the particles, because density of particles is higher than the aluminum–11.8% Si alloy (the density of LM6 is 2.65 grs c^{-3} and of TiC is 4.93 grs c^{-3}) and hence the increase in wt% of TiC will increase the density of the composite based on the role of mixtures (Premkumar and Chu, 1995).

8.1.1 Tensile test

Tensile strength of titanium carbide particulate composites are determined. The tensile strengths of 2 and 0.2% weight fraction of the above combined particulate composites are 135.8325 and 116.0743 MPa for a composite without vibration and 135.8454 and 118.68 MPa for a composite with vibration respectively. It would appear from the results that the tensile strength values are increased with the increasing on the weight fraction % of the titanium carbide in the alloy matrix and the tensile strength increased for the casting of the vibration, when compared to the gravity die castings (**Table 11**). The tensile strength values are increased gradually when the above combination of particulate weight fraction addition of LM6 alloy matrix is increased (see **Figure 13**).

The mechanical properties of the as-cast TiC particulate composite have demonstrated a strong dependence on the particulate percentage and the fabrication process and the frequency of vibration. A correlation between the TiC content and the tensile strengths was seen, and generally, the strength increased to a maximum of about 135.8325 and 135.8454 with and without vibration.

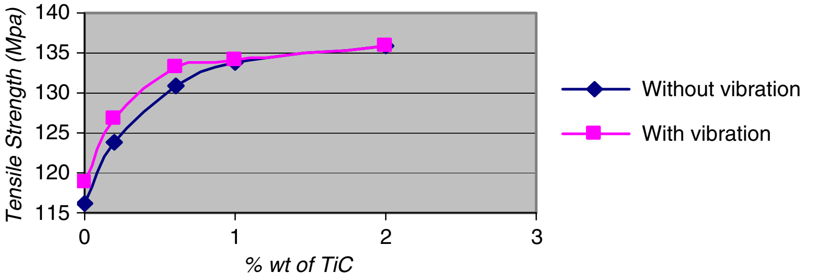

Figure 13 Average of tensile strength versus weight fraction of TiC with and without vibration.

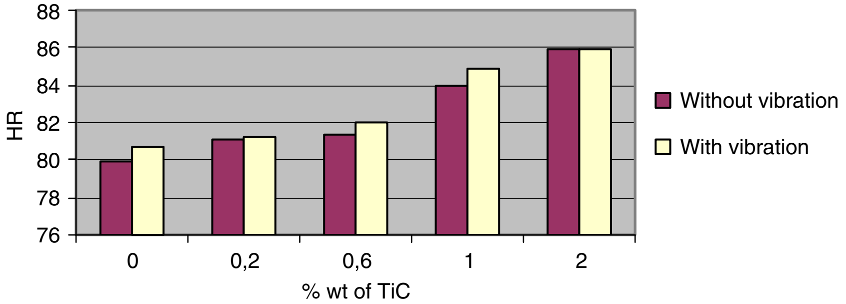

Figure 14 Average hardness Rockwell vs. weight fraction of TiC with and without vibration.

8.1.2 Hardness measurement

The data on the hardness of combined particulate reinforced composites made in sand mold was analyzed. It is found that the hardness value increased gradually with the increased addition % by weight with and without vibration and it is shown in **Figure 14**. The maximum hardness value based Rockwell superficial 15N–S scale is 85.88 for 2% without vibration and 85.96 with vibration.

Based on **Figure 12**, the variation in the hardness value of the composites corresponding to the variation in the weight fraction of the titanium carbide particulate can be known. Moreover, the hardness values of the processed composites increases with the increasing in addition of titanium carbide particulate by weight fraction %. Regarding the hardness results, hardness is much higher for the vibrated 10.2 Hz. It is clearly shows a tendency of increasing properties from 0.2, 0.6, 1 and 2 %wt of TiC in all the composite process.

8.1.3 Fractography

The fracture surface investigation of composite samples is performed by using HITACHI S-3400 N variable pressure microscope with Inca 300 Energy Dispersive X-ray (EDX). By using it, fracture surfaces of the tensile tested samples are observed at higher magnifications to characterize the type of failure. Then, studies on the interphase and bonding are performed to observe the formation of interfacial reaction products, to predict the type of bonding between the particulate surface, and the matrix surface. The examined fracture surface of LM6 matrix composite surfaces is exhibited a brittle cleavage fracture mechanism. The fracture surface of the grain refined composite showed broken aluminum and TiC particles (**Figure 15**) and well-attached particles within the dimples, indicating rather good interface cohesion between matrixes and reinforcing particles.

From the SEM observation of wear surface, no crack was existed in the interface between the particle and the matrix, nor within any particle, but the surface of the composite with vibration better than without vibration. This further confirmed the strong bonding between the matrix and the TiC particles, so the dispersed TiC particles could have load carrying capability in the composite and could provide protection to the alloy matrix (Shyu and Ho, 2006).

8.2 Thermal Conductivity and Diffusivity

The values of density in composites increase with increasing weight fraction of the particles and with using vibration mould during solidification, because density of particles is higher than the aluminum–11.8% Si alloy (the density of LM6 is 2.65 grs c^{-3} and of TiC is 4.93 grs c^{-3}) and hence the increase in wt% of TiC will increase the density of the composite based on the role of mixtures (Premkumar and Chu, 1995; Sayuti *et al.*, 2011a,b,c,d,e). Mechanical vibration makes solidification microstructure of aluminum matrix composite fine and homogeneous and decrease the amount of defect such as shrinkage cavity and inclusions. The effect of vibration to help in the promotion of nucleation and thus reducing as-cat grain size, reducing hydrogen, reducing shrinkage

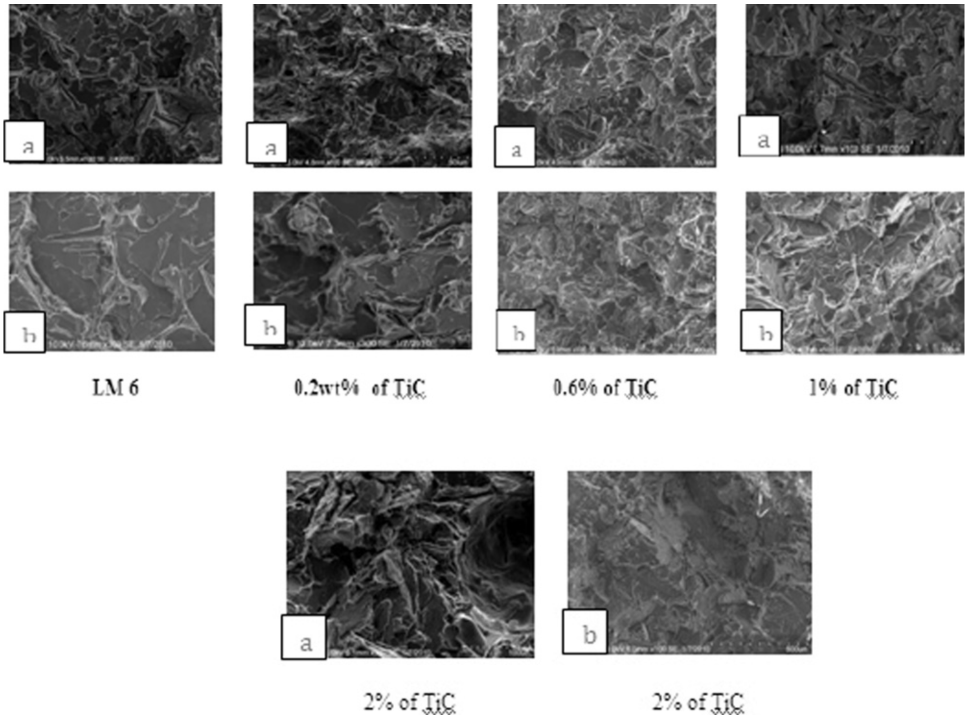

Figure 15 SEM images of tensile fractographs of Al–TiC composite. (a) Without vibration and (b) with vibration.

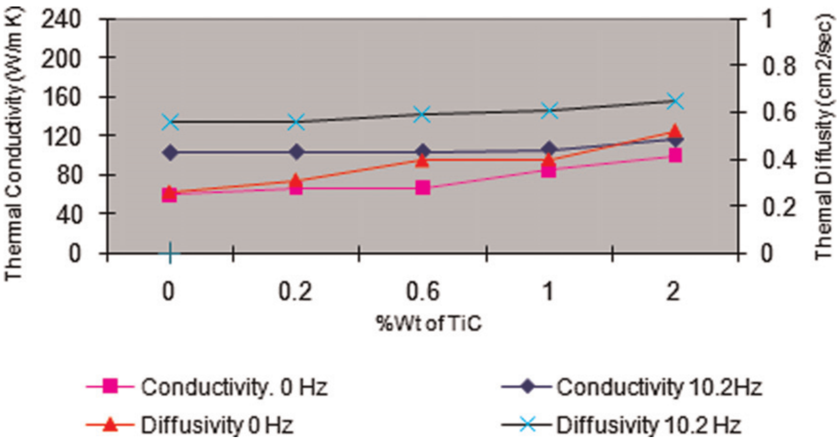

Figure 16 Thermal Diffusivity and Conductivity of Al–TiC particulate composites.

porosities due to improved metal feeding, and producing a more homogenous composites structure (Chirita *et al.*, 2009; Kocatepe and Burdett, 2000; Xu *et al.*, 2008).

Figure 16 shows the influence of mechanical vibration and various percentage of TiC on thermal conductivity of Al–TiC particulate composites. As expected, the thermal conductivity for Al–TiC composite increase with increasing percentage of TiC. The thermal conductivity of TiC is much larger than that Al, so the addition of TiC to Al matrix will result in an increased in thermal conductivity of the composite. The thermal conductivity of aluminum–matrix composites also depends on the particulate and its weight fraction, the alloy matrix heat treatment condition, and the filler matrix interface. From the microstructure study, it can be seen that the particle distribution and aluminum contact is improved by increasing content of TiC and frequency of vibration. Mechanical vibration can enhance the compatibility between the matrix and the particles thus enhance the dispersion of the particles, improved wet out between the matrix and particles which in turn improve the thermal conductivity ability of the Al–TiC particulate composites. Comparison between morphology of with and without vibration and various percentage of TiC particulate is shown in **Figure 17**.

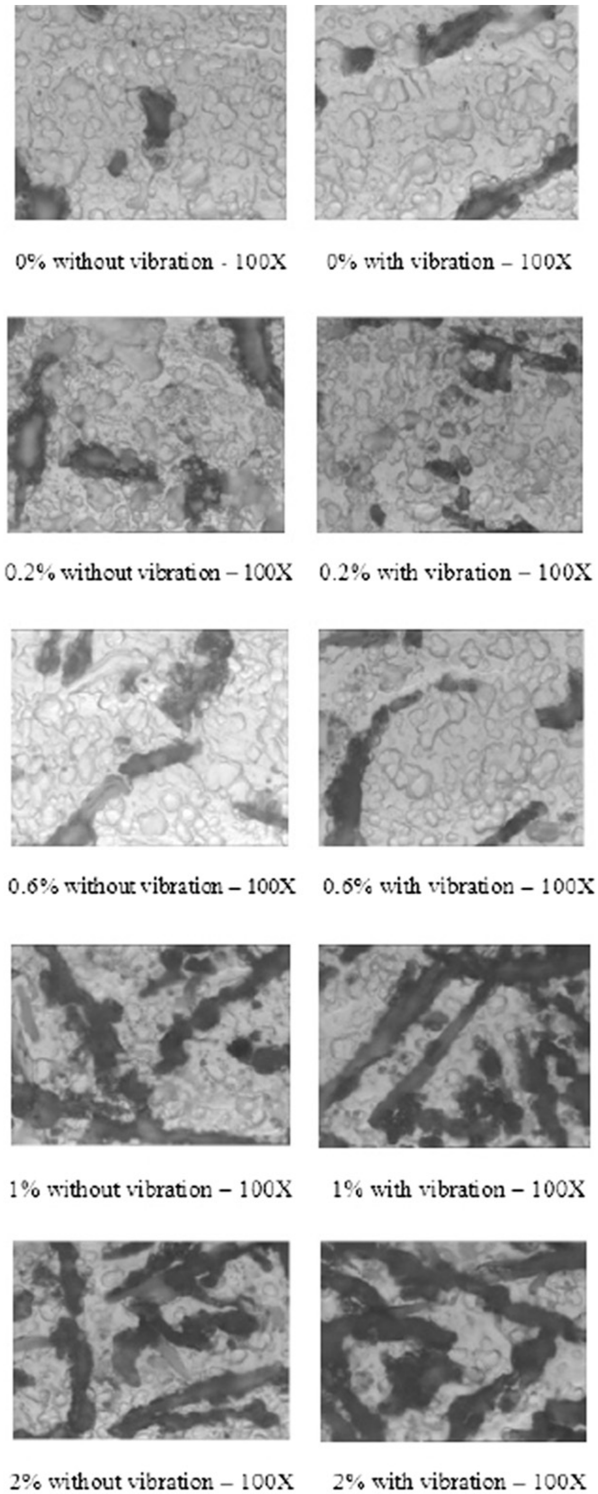

Figure 17 Microstructure of Al–TiC particulate composite without and with vibration (10.2 Hz).

9 Conclusions

Based on the findings of the research, the conclusions and suggestions are given for further improvement of the research work. Alternative composite preparation methods are suggested to get better particulate reinforced aluminum/11.8 wt%silicon alloy matrix composite cast products.

a. It is concluded that the mechanical vibration mould for solidification is an efficient and cost effective liquid metallurgical processing technique for preparing particulate reinforced metal matrix composite castings.
b. Particulate preheating has improved the wettability of the composites, hence good quality composites are manufactured by applied mechanical vibration mould during solidification. The particulates are preheated up to 200 °C for 2 h in a muffle furnace.
c. Pouring temperature is a critical factor in metal matrix composites processing and the composite slurry is poured at 850 °C in the sand mould with and without vibration at various frequency.
d. Mixing time in the crucible containing the mixture is an important factor, since it may leads to sticking with the impeller blade if more mixing time is allowed. The composite slurry is mixed in the crucible nearly for 10 s and immediately transferred into the sand molds.
e. Delayed pouring causes drop in temperature which leads to incomplete mold filling and casting defects. Faster pouruing has eliminated all these problems.
f. The tensile properties of the LM6/TiC MMC for different weight fractions at ambient temperature reveals an increases in tensile strength and Young's modulus with increase in reinforcement content in the LM6 alloy matrix.
g. The mechanical properties of the composite with vibration are always better than those without vibration. The impact energy value increases with increase in percent weight fraction of TiC and also with using vibration during solidification Mechanical vibration enhances the solidification process and more fine and homogeneous microstructures are formed. It also decreases the defects such as part shrinkage and inclusions. The effect of vibration to help in the promotion of nucleation and thus reducing as-cat grain size, reducing hydrogen, reducing shrinkage porosities due to improved metal feeding, and producing a more homogenous composites structure. These improved features lead to improved mechanical properties and lower susceptibility to cracking.
h. The mechanical vibration and the weight fraction of the reinforcement particles has affected the density. It is easy to draw a conclusion that, by mechanical vibration during solidification, the size of shrinkage cavity and inclusion are reduced and the amount of defects is also decreased. It was found that the density is higher in the sample with mechanical vibration mould than in without vibration mould. It is obvious that the amount of defect such as shrinkage cavity and inclusion is decreased and the compactness is enhanced due to applied mechanical vibration during the solidification process. The values of density in composites also increase with increasing weight fraction of the particles, because density of particles is higher than the aluminum–11.8% Si alloy (the density of LM6 is 2.65 g cc^{-1}) and of TiC is 4.93 gm cc^{-1} and hence the increase in wt% of TiC will increase the density of the composite based on the rule of mixtures.
i. The hardness value of the titanium carbide reinforced LM6 alloy MMC increased with the addition of titanium carbide particulate in the matrix. The mechanical behavior of the processed composite had a strong dependence on the weight fraction addition of the second phase reinforcement particulate on the alloy matrix. The result increase.
j. Thermal conductivity of Al/TiC particulate MMC has increased with an increasing particles and applied vibration during solidification. It was found that 10.2 Hz of vibration is able to produce good dispersion of particles in the matrix, increase in density, improve thermal conductivity, while maintaining the improved mechanical properties. This research proved that there is possible to increase thermal conductivity of metal matrix composite even at low vibration and filler concentrations.

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