CHAPTER 2

LITERATURE REVIEW

2.1 OVERVIEW

This chapter gives an insight into the understanding of the state-of-the-art of aluminium metal matrix composites for the following:

- Fabrication
- Mechanical properties
- Tribological studies
- Machining studies
  - Drilling studies
  - Milling studies
  - Electrical Discharge Machining

Metal Matrix Composite (MMC) has found increasing usages in industry for the purpose of lightweight and high-strength applications. This work addresses the requirement of a light weight metal matrix composite material in automotive and aerospace applications. It emphasizes the improvement of the properties of the aluminium alloy materials and productivity of aluminium metal matrix composites.

Aluminium alloys have been gaining great importance as structural materials, but for many applications, it is necessary to improve their wear resistance. In particular, usage of aluminium alloys in automotive applications has been limited due to their inferior strength, rigidity and wear resistance, as compared to those of ferrous alloys. Particulate reinforced aluminium composites, nevertheless, offer reduced mass, high stiffness and strength,
improved wear resistance, etc. Specifically, the possibilities of substituting iron-base materials with Aluminium Metal Matrix Composites (AMMCs) in automotive components provides the potential for considerable weight reduction.

In the present work, ‘Processing and Performance Characteristics of Aluminium Alloy based Metal Matrix Composites’, new aluminium alloy - aluminium oxide / silicon carbide composites of different compositions are developed by a new combination of vortex method and the pressure die casting technique. The improved properties of these new aluminium alloy - aluminium oxide and aluminium alloy - silicon carbide composites can be used to bring the advantages to many engineering applications especially in the automobile and aerospace industries. Hence, the literature review describes the present status of the fabrication, mechanical properties, tribological studies, drilling studies, milling studies and electric discharge machining studies of the aluminium alloy – alumina / silicon carbide metal matrix composites.

2.2 LITERATURE REVIEW

2.2.1 Literature Related to Fabrication

Aluminium alloy reinforced with discontinuous ceramic reinforcements is rapidly replacing conventional materials in various automotive, aerospace and automobile industries (Allison and Cole, 1993). Composite materials were named as the ‘materials of the future’ in the 1970’s when they were introduced in engineering applications (Foltz and Blackman 1997). Due to lightweight and high strength applications, metal matrix composite has found increasing usage in industry. Kang and Seo (1996) found that aluminium 2024 matrix had poor fluidity compared with a casting of aluminium alloy. Aluminium alloys are ready to cast by all common casting techniques (Budinski 2001). Papworth and Fox (1998) identified the effect of oxide defects in most aluminium castings during the casting process and
suggested that the addition of a small amount of bismuth to the aluminium alloy would stop the formation of this type of defect in the casting. Tham et al (1999) investigated the synthesis of Al–SiC particulate reinforced metal matrix composites by the Disintegrated Melt Deposition (DMD) technique, here the SiC reinforcement was mixed with the liquid aluminium matrix by a mechanical agitation process.

Due to their excellent castability and good compromise between mechanical properties and lightness, aluminium – silicon alloys are the most important and widely used casting alloys to cast components with complex shapes. Further more the application of aluminium alloys in the automotive sector could be one of the economically sustainable innovations (Mattia Merlin et al, 2009). Mohamed et al (2009) found that the aluminium – silicon alloy properties were influenced by the shape and distribution of the eutectic silicon particles in the matrix, and also by the iron intermetallics and copper phases that occur upon solidification. The function of Fe, Mn, Cu, and Mg content was more sensitive to variations in microstructure and tensile properties of Al – Si near - eutectic alloys.

Aluminium – Silicon (Al–Si) alloys were widely used as engineering materials due to their light weight, ease of fabrication, high strength to weight ratio, excellent castability, corrosion resistance, good weldability, good thermal conductivity and wear resistance properties. Therefore they are well suited for the aerospace, automobile, and military applications (Anasyida, et al, 2010). Near - eutectic Al – Si alloys exhibit good castability, high wear resistance, low density and thermal expansion coefficient. Therefore, these alloys are used in transportation vehicle components in which tribological properties are important. It is well known that the wear resistance of Al–Si alloy is influenced by factors such as load and speed as well as by microstructural parameters such as the morphology and volume fraction of the silicon phase. Further,
improvements in the wear properties of these alloys can be achieved by incorporating hard ceramic particles such as Al$_2$O$_3$, SiC and TiB$_2$ to produce composites (Daoud et al, 2004).

Hashim et al (1999) evaluated the difficulties associated with attaining a uniform distribution of reinforcement, good wettability between substances, and a low porosity for the production of silicon carbide-aluminium alloy MMCs under low cost stir casting technique. Wettability of the reinforcement particles by the matrix alloy and especially reinforcement of ceramic particles were very difficult to wet by liquid metal (Hashim et al, 2001a). Hashim et al (2001b) have chosen magnesium as a wetting agent and stirring was done continuously, while slurry solidifying was found to promote the wettability of SiC. Decreasing solidification time was also found to improve the wettability. Naher et al (2003) developed a simulation technique to the parameters for uniform particle distribution of SiC in aluminium matrix composites for batch compocasting and found that higher blade angles and lower viscosity resulted in a reduction of particulate dispersion time and minimum stirring speed depends upon the viscosity of the matrix liquid. Ravi et al (2007) investigated and optimized the influence of mixing parameters like impeller blade angle, rotating speed, direction of impeller rotation and effect of baffles on the synthesis of Al–SiC$_p$ reinforced Metal Matrix Composites (MMCs) by the stir casting technique through a water model.

Singh et al (2001) fabricated an aluminium alloy MMC by using a natural mineral namely sillimanite as a reinforcement through a solidification technique. The reinforcement particles were added into the matrix melt by creating a vortex with the help of a mechanical stirrer and the melt temperature was maintained between 750 °C and 800 °C. In the cast composite, sillimanite particles were uniformly distributed and exhibited good mechanical bonding with the matrix. The strength of the composite was marginally lower than that
of the base alloy but the hardness and the wear resistance of the composite were found to be significantly higher than the base alloy. Velhinho et al (2003) observed that as a consequence of centrifugal casting SiC particles were partially clustered with some pores gathered with them, and this was being associated to imperfect wetting of ceramic particles by the molten aluminium alloy. Moreover, small spherical pores associated with trapped gas bubbles were observed in the matrix. Sahin (2003a) developed an aluminium alloy composite with SiC particles by molten metal mixing and squeeze casting method. The molten mixture was poured into a die after stirring and metal matrix composites were produced by applying pressure. It was observed that uniform dispersion of particles occur in the matrix alloy and also density decreased with decreasing particle size. Akhlaghi et al (2004) developed aluminium alloy - SiC composite by compocasting techniques. The uniformity in the particle distribution was improved by increasing the SiC particles, at the expense of increased porosity content, with increasing the size of the particle.

Seah et al (2003) developed Al / quartz particulate composites cast in sand moulds containing metallic and non-metallic chills respectively. During testing, all other factors were kept constant and by the introduction of chills, the faster heat extraction from the molten MMC during casting led to an increase in the ultimate tensile strength and fracture toughness of the castings. In fracture analysis of the MMCs, cast using copper and steel chills showed ductile rupture with isolated micro-cracks and a bimodal distribution of dimples on the fracture surface. In contrast, fracture analysis of the MMCs cast without chills revealed brittle failure with separation of the quartz particles from the matrix.

fabricated in situ Al$_2$O$_3$ decomposed from Al$_2$(SO$_4$)$_3$ reinforced aluminium matrix composites through stir cast by adding Al$_2$(SO$_4$)$_3$ to the molten alloy, which was the raw and processed materials from which high purity Al$_2$O$_3$ was made. Production cost may be reduced but SO$_3$ decomposed from Al$_2$ (SO$_4$)$_3$ produced Particulate Metal Matrix Composite (PMMC) with fine and uniformly distributed particulates, and hence with good microstructure / properties, better bonding between Al$_2$O$_3$ and matrix occurred. Cast defects such as gas hole, porosity and particles segregation were not found. Ourdjini et al (2001) found that settling of the particles influenced the microstructure of the composite during liquid processing of composites. At low melt temperatures, the volume fraction of particles did not affect the rate of settling, but as the melt temperature increases, the particles tend to settle when presented in lower volume fractions. Balasivanandha Prabu et al (2006) identified that the stirring speed and stirring time influence the microstructure and the hardness of the aluminium alloy – silicon carbide metal matrix composite material. Bindumadhanva Prabu et al (2001) produced cast A356-SiC$_p$ metal matrix composites with SiC particle reinforcement by the melt stirring technique. The uniformity of distribution of SiC particles and porosity were found to improve with increasing SiC content. Particle porosity interaction (clustering) was observed to be greater for low SiC content composites as compared to higher SiC content composites.

Zaklina Gnjidic et al, (2001) produced Al alloy reinforced with SiC particles composites by hot pressing. Addition of the SiC particles increased the yield strength and elastic modulus. Lim and Clegg (1997) developed a new process referred to as the 'hybrid process’ combining the advantages of the squeeze casting and investment casting processes for the production of Al-Si alloy metal-matrix composites. During the tensile testing, these MMCs had
superior strength than the MMCs produced by squeeze casting and investment casting individually.

The most popular reinforcements are silicon carbide and aluminium oxide. Aluminium, titanium and magnesium alloys are commonly used as the matrix phase. The densities of most of the MMCs are approximately one-third of steel resulting in high specific strength and stiffness. These potentially attractive properties of MMCs coupled with the ability to operate at high temperatures, enable the MMCs to compete with super alloys, ceramics and re-designed steel parts in several aerospace and automotive applications (El-Gallab and Sklad, 1998). Konopka and Szafran (2006) fabricated Al$_2$O$_3$–Al composites by metal infiltration into porous preforms. This technique provided a homogeneous distribution of metallic phase in the ceramic matrix and designed for their strength and toughness. Peng Yu et al (2004) found that the distribution of the alumina particles strongly depends on the rate of cooling of the sintered product.

In situ Al$_3$Ti particle reinforced aluminium metal matrix composites, with reinforcing particles dispersed in the aluminium matrix homogeneously, had strong ability to nucleate aluminium grains. This also made the interfacial bonding between these two phases strong. Particle size and morphologies were largely affected by the processing conditions, such as temperature, holding time and the composition of the flux. High temperatures and longer holding times resulted in the coarsening of the particles (Xiaoming Wang et al, 2004). Kok (2005) developed 2024 aluminium alloy metal matrix composites reinforced with Al$_2$O$_3$ particles and found that the porosity in the composites increased with increasing weight fraction and decreasing size of Al$_2$O$_3$ particles. Moreover, the dispersion of the coarser sizes of particles was more uniform while finer particles led to agglomeration of the particles and porosity, the hardness and tensile strength of the composites increased with decreasing size and increasing weight fraction of particles.
Conventional practice for the preparation of Al–Si alloy-based composites involves the addition of particles such as SiC to the liquid aluminium by techniques like stir casting which could lead to segregation of reinforcement particles and poor adhesion at the interface, unless the matrix and/or particles were suitably modified (Kumar et al., 2008). Lloyd (1994) reported that vortex mixing technique was suitable for the preparation of ceramic particle dispersed aluminium composite. The vortex mixing technique, for the preparation of ceramic particle dispersed aluminium matrix composites, was developed by Surappa and Rohatgi (1981). The stir casting involves incorporation of ceramic particulate into liquid aluminium melt and allowing the mixture to solidify. Here, the crucial aspect is to create good wetting between the particulate reinforcement and the liquid aluminium alloy melt. The simplest and most commercially used technique is known as vortex technique or stir casting technique. The vortex technique involves the introduction of pre-treated ceramic particles into the vortex of molten alloy created by the rotating impeller (Surappa, 2003).

With the development of die casting technology, High Pressure Die Casting (HPDC) is widely used to produce near net shaped components of aluminium alloys. This process allows the injection of molten alloy into a die cavity with a high velocity and enables rapid solidification. Lee and Lee (2000) performed the die casting processes using a preheated die at the pouring temperature of 700 °C. From that, it was found that the SiC particulates were homogeneously distributed in Al alloy matrix, resulting from the refinement of cell size due to rapid cooling rate. The tensile strength of the as-die-cast composite was higher than that of the as-die-cast aluminium alloy. Furthermore, the tensile strength slightly increased with increasing SiC particulate volume fraction.
The development of the pressure die-casting process should have a priority over other metal-casting technologies, since it ensures the production of thin walled cast articles of a complicated shape with a high yield and high dimensional precision. Such products effectively do not need further mechanical treatment (Unigovski and Gutman, 1999). Pressure Die Casting (PDC) is a process ideally suited to manufacture mass produced metallic parts of complex shapes requiring precise dimensions. In this process, molten metal is forced into a cold empty cavity of a desired shape and is then allowed to solidify under a high holding pressure. The entire cycle can be divided into three stages, the first or slow speed stage, the second or high speed stage and the third or intensification stage, where hydraulic pressure is exerted to avoid shrinkage or gas problems. The high pressure die comprises two basic parts, the fixed half and the moving or ejector half. When the die is opened, the casting is retained in the moving half, from which it is ejected by pins, activated either hydraulically or mechanically (Tsoukalas, 2008).

In high pressure die casting, molten metal is injected into a die cavity at a high velocity. The metal entering into the cavity expels the air from the cavity through the vents. Air back pressure will be created when the volume of metal flow exceeds the volume of air escaping out of the die cavity. A new mathematical model for the calculation of the creation of the back pressure in a die cavity was proposed by Lee and Lu (1999). Pfohl et al (1999) investigated the use of large amounts of lubricant to decrease the surface quality of the aluminium precision parts in pressure die casting. The deposition of wear resistant coatings provided a means of minimising the use of lubricants while at the same time increasing the lifetime of the die casting tools.

The attractiveness of die casting is its ability to make near net shape parts with tight tolerances and requiring little or no machining. The most commonly used die casting process is high pressure die casting with high rates
of production. The automotive industry uses an extensive range of aluminium HPDC parts including transmission housings, cylinder heads, inlet manifolds and engine sumps as well as decorative trim. This trend is increasing as replacement of steel parts with lighter aluminium High Pressure Die Casting (HPDC) parts (Tharumarajah, 2008). HPDC is a popular and cost effective method for mass production of metal components where physical dimensions must be accurately replicated and surface finish is important. Approximately half of all castings worldwide made from aluminium alloys are manufactured in this way and these are used for a wide range of automotive parts and other consumer goods (Lumley et al, 2008).

Huseyin Sevik and Can Kurnaz (2006) produced Al₂O₃ particles reinforced aluminium MMCs using pressure die-casting technique. The density values of the composites were increased by adding Al₂O₃ particle. The hardness of the composites was increased with increasing particle volume fraction and with decreasing particle size. The tensile strength of the composites decreased with increasing particle volume fractions and size. The wear rate of the composites decreased with increasing particle volume fraction and with decreasing particle size but increased proportionally to the applied load. Wear mechanism for the surface of the un-reinforced alloy was plastic deformation, whereas for the composites it was the layer deformation on the surface of the composites.

The Rheo Die Casting (RDC) process is an innovative semisolid processing technique for manufacturing near net shape components. The process innovatively adapted the well established high shear dispersive mixing action of the twin screw mechanism to the task of in situ creation of semisolid metal slurry with fine and spheroidal solid particles followed by direct shaping of the semisolid metal slurry into a near net shape component using the cold chamber die casting process. Experimental results showed that the RDC
samples had extremely low porosity, fine and uniform microstructure throughout the entire casting, and consequently much improved strength and ductility, compared with those produced by the HPDC process and other semisolid processes (Fan, 2005). Immiscible Al–Si–Pb alloys were successfully produced using rheo die casting process. This process produced a uniform dispersion of Pb particles in an Al-alloy matrix. It was also found that both the ultimate tensile strength and elongation of Al–Si–Pb alloys decreased with increasing Pb content (Fang and Fan, 2006).

Yuelong Bail et al (2008) studied the effects of slurry temperature, injection pressure, and piston velocity on the rheo filling ability of semisolid A356 alloys produced by the RDC method and found that the slurry temperature had an important effect on the filling ability and it was better at higher slurry temperature. Piston velocity and the injection pressure also had a great effect on the filling ability to the high quality die casting.

Megumi Kawasaki et al (2005) developed Al-6061 metal matrix composite reinforced with fine Al₂O₃ particulates and was processed by equal channel angular pressing. Micro structural observations showed that the grain size was reduced but the average particulate size was unchanged. Morteza Eslamian et al (2008) developed a new technique to produce metal matrix composites by injecting silicon carbide particles into molten aluminium just prior to centrifugal atomization.

2.2.3 Literatures Related to Mechanical Properties

Metal Matrix Composites (MMCs) are a new class of material that consist of a non-metallic phase distributed in a metallic matrix with properties that are superior to those of the constituents. The principal reasons for the use of these materials are light weight, low density and load bearing applications on account of their enhanced mechanical properties. Their high thermal
conductivity and low thermal expansivity also rendered them suitable for automotive brake applications (Durantea et al, 1997).

Discontinuously reinforced metal matrix composites have proved to be promising as hi-tech structural and general engineering materials because of their higher specific modulus, strength, thermal stability, and improved tribological properties over their conventional monolithic counterparts. Aluminium base matrix composites with ceramic particle reinforcements combine the high ductility and toughness of aluminium with the high modulus and tensile strength ceramics. These MMCs are primarily particulate reinforced aluminium alloys and the composite is typically an aluminium alloy reinforced with SiC or Al₂O₃ (Baki Karamis and Fehmi Nair, 2008).

Antonio Forn et al (2003) suggested that decohesion between the matrix and reinforcement involved a loss of mechanical properties. The spinel creation came about during the casting process promoting the loss of adherence between the aluminium matrix phase and the reinforced Al₂O₃ particles. Zhu and Iizuka (2003) fabricated porous ceramics with a framework of aluminium borate whiskers by in situ firing ceramic powder compacts, and incorporated within an Al alloy matrix by squeeze casting. They found that the microstructures of the porous aluminium borate and the composites were isotropic and independent of the compaction and the casting direction. The hardness and the tensile strength of the Al alloy matrix composite increased with increasing volume fraction of porous aluminium borate with decreasing diameter of aluminium borate whiskers. The tensile strengths of the composite were higher than those of un-reinforced Al alloy.

Soon-Jik Hong et al (2003) have conducted tension tests on Al-SiC composites and showed that, the yield strength and ultimate tensile strength increased, and the fracture strain decreased due to the addition of SiC.
Raghukandan et al (2003) used the high explosive under water shock waves to consolidate the carbon fibre reinforced aluminium composites using an axisymmetric under water assembly. The encapsulation of the fibre detritus in the aluminium matrix resulted in high hardness. Shen and Chawla (2001) studied the correlation between macro hardness and tensile strength of particle reinforced metal matrix composites. The matrix strength appears to play an important role in influencing the behaviour of the composite under hardness and tensile loading conditions. Gudena and Hall (2000) carried out the compression test on aluminium metal matrix composite reinforced with continuous unidirectional $\text{Al}_2\text{O}_3$ fibres and found that the maximum stress of the composite increased with increasing strain rate.

Since the amount of graphite increases in the aluminium - SiC / graphite hybrid composite, wear rate of the composite increases up to 5% and turn at 8 % (Ted Guo and Tsao, 2000). Shen et al (2000) suggested that the hardness does not necessarily scale with the tensile strength of the composite. This is particularly true for composites with large reinforcement particles which are prone to fracture during deformation processing and / or tensile testing. Vassel (1999) analysed the mechanical properties of unidirectional reinforced titanium based (Ti–MMCs) and aluminium-based (Al–MMCs) composites. Both Ti–MMCs and Al–MMCs offer outstanding tensile characteristics in the longitudinal direction but it lies in their low transverse properties due to the weak fibre / matrix bond. This low transverse strength in Al–MMCs can be alleviated by the use of cross-ply laminates.

Mohanty et al (2008) developed aluminium – boron carbide composite with boron carbide particulate reinforcement in an aluminium matrix. From the result, it was noted that the microstructure showed the existence of porosities. The hardness and brittle fracture increased with higher reinforcement fractions. Ceschini et al (2006) performed the tensile tests on
aluminium alloy reinforced with different percentage volume of $\text{Al}_2\text{O}_3$ particles. The results showed that a significant increase in the elastic modulus and tensile strength in the MMCs with respect to the unreinforced alloys were evident from the tensile tests.

Srivastava et al (2005) found that the aluminium alloy based metal matrix composites, containing SiC$_P$ as reinforcement, possess physical and mechanical properties which have been used for applications in aerospace and automotive industries. Huseyn Sevik and Can Kurnaz (2006) analysed the hardness, density and mechanical properties of the LM6 aluminium silicon alloy composites fabricated with alumina reinforcement. Karantzalis et al (1997) developed the metal matrix composites by the addition of TiC particles to molten aluminium by a proprietary process with reasonably homogeneous and extensive grain refinement. Elastic modulus increases per volume percent of reinforcement added, are greater for Al-TiC composites than that of commercial Al-$\text{Al}_2\text{O}_3$ and Al-SiC; powder or liquid - route manufactured composites. Cavaliere (2005) developed the aluminium alloy reinforced with of alumina particles by friction stir process and showed good strength and ductility values.

A controlled amount of molten metal was poured into the preheated die with the preheated preform and then die pressure was applied until complete solidification was achieved. Thus, short fibre reinforced MMCs were fabricated by the forced infiltration of molten metals into a fibre preform under an appropriate injection velocity. Microstructures of the fabricated preform and the dispersion states of the fibres were observed. The preform deformation behaviours, breakage of the fibres and the hardness of the fabricated composites were analyzed by Kang and Yun (1996). Rabiei and O’Neill (2005) developed composite foam and identified that it had superior compressive strength and energy absorption capacity.
Jichun Ye et al (2005) developed a tri-modal aluminium based composite with 10 %wt of B₄C, 50 %wt coarse-grained Al and the balance nanocrystalline Al. It was found that the composite was extremely high in strength in compression but had low ductility at room temperature. William Speer and Omar S. Es-Said (2004) reported on aluminium – beryllium metal matrix composite, having high modulus and low density combined to reduce the size and weight of many structural aerospace components. Zhang et al (2004) fabricated aluminium boron carbide composites by two different powder consolidation routes of extrusion and sintering / hot isostatic pressing. The strength of the MMCs increased with increasing volume fraction of particulate reinforcement.

The presence of discontinuously reinforced Silicon Carbide Particulates (SiCₚ) in aluminium alloy increases the strength of the composite, but an increase in test temperature decreased the elastic modulus and strength of the composite. The presence of the hard, brittle and elastically deforming SiC particles in the soft, ductile and plastically deforming aluminium alloy metal matrix caused fine microscopic cracks to initiate at low values of applied stress. Fracture of the matrix between the clusters of reinforcing particles coupled with particle failure by cracking and decohesion at the matrix particle interfaces, allowed the microscopic cracks to grow rapidly and link resulted in macroscopic failure and low tensile ductility (Srivatsan et al, 2003). Chawla et al (2002) developed a sinter-forging approach to fabricate particle reinforced metal matrix composites and it exhibited uniform distribution of SiC particles, higher Young’s modulus and ultimate tensile strength than the extruded material, but lower strain-to-failure was caused by poorer matrix inter-particle bonding.

Closed die hot forging of aluminium - silicon alloy particulate silicon carbide reinforcement and unreinforced matrix alloy samples was carried out.
The microstructure and mechanical properties of the matrix alloy and the composite samples were investigated, which showed that forged microstructures had more uniform distribution of the SiC particles and the eutectic silicon in comparison to the as-cast microstructures. Evaluation of the mechanical properties showed that the forged samples had strength values superior to those of the as-cast counterparts and yield strength. Further, the tensile strength of the matrix alloy and composite samples were increased (Ismail Ozdemir et al, 2000). Shen et al (2001) indicated that a simple relationship between hardness and tensile strength did not exist in MMCs, the induced particle fracture greatly reduced the tensile strength, and it did not significantly affect the deformation under indentation loading. At very low matrix strengths, the composites exhibited similar tensile strengths but the hardness increased with increasing particle concentration and the particle fracture caused by tensile testing was independent of matrix strength.

Razaghian et al (2009) studied the effect of strontium in two A357 aluminium metal matrix composites reinforced with fine particles of silicon carbide and alumina separately. Results showed that the addition of 0.03% strontium made a modest improvement to the yield strength, ultimate tensile strength, elongation percentage values, and the scatter of these properties, but made a significant improvement to minimum strength and elongation results. Further results showed that the addition of higher strontium levels contributed to the over modification of the eutectic silicon and promoted the formation of an Al–Si–Sr intermetallic compound on the particle / matrix interface.

Padmanabhan et al (2004) analysed the mechanical behaviour of Al - SiC thin walled tubular composites. Aluminium reinforced glass matrix composite exhibited good mechanical properties (Bernardo et al, 2004). Microstructure analyses and tensile tests of heat-treated Al - 5SiO₂ showed a strong interfacial bonding between the fibres and the matrix (Gregolin et al,
2004). Hayrettin Ahlatci et al (2006) investigated pure Al and Al–Mg alloy matrix hybrid composites and found that addition of magnesium increased the matrix hardness, wear resistance but decreased the porosity.

2.2.3 Literatures Related to Tribological studies

The major driving forces behind the development of Al–Si cast alloys were the superior wear resistance, low Coefficient of Thermal Expansion (CTE), high corrosion resistance, high strength to weight ratio and excellent castability. Due to this Al-Si cast alloys made them potential candidate materials for a number of tribological applications in automobiles and other engineering sectors. The improvement in sliding wear resistance and mechanical properties was dictated by the type, shape, size and distribution of second phase particles in the matrix. Hardness was usually thought of as a wear controlling property, i.e. the higher the hardness, the greater is the wear resistance of the material. However, it should be emphasized that it is the hardness of the contacting asperities and not the bulk hardness that will control the wear rate. The addition of hard second phase particles to the matrix improves both wear resistance and mechanical properties (Basavakumar et al. 2009). Rao et al (2009) studied the dry sliding wear behaviour of aluminium alloy and aluminium alloy - SiC composite using pin-on-disc apparatus against EN32 steel counter surface, and observed that the wear rate of the aluminium alloy was significantly higher than that of the aluminium alloy - SiC composite and is suppressed further due to the addition of silicon carbide particles.

Hardness, compressive strength and wear resistance of the aluminium metal matrix composites can be improved by the addition of Al₂O₃ and Al₆C₃ (Abouelmagd, 2004). Natarajan et al, (2009) focused towards the particulate reinforced metal - matrix composite for tribological applications, due to the advantages of MMCs such as, good sliding wear resistance, high
load carrying capacity and low density. Metal matrix composites containing a high volume fraction of carbide, nitride, boride, or oxide particles were frequently the materials of choice for applications that require good wear resistance.

Aluminium alloys are promising structural materials due to their high specific strength and stiffness which have been used in automobile industries as structural components of internal combustion engines, e.g. cylinder blocks, cylinder heads, and pistons. However, their applications are restricted because of their poor wear resistance. To improve wear resistance of common aluminium alloy, metal matrix composites reinforced with discontinuous ceramic reinforcements have received extensive attention due to their superior mechanical properties (Du Jun et al, 2004). Due to the SiC particle reinforcement in aluminium, the presence of SiC improved the friction and wear behaviour of Al - SiC composites (Venkataraman and Sundararajan, 1996 a, b). Hong Chang et al, (2010) studied the dry sliding wear of Aluminium Matrix Composites (AMCs) reinforced with ceramic particles or fibres. From that, it was found that AMCs generally exhibited superior wear resistance compared to their matrix; with increases in the ceramic particle size or its volume content, the wear resistance of the AMCs further improves.

Metal Matrix Composites (MMCs) generally possess superior wear resistance compared with the unreinforced aluminium alloys. The wear parameters that control the friction and wear performance of reinforced aluminium composites could be classified into physical factors and material factor. The physical factors such as sliding speed and normal load, and the material factors such as volume fraction and size of reinforcement had been evaluated by the sliding behaviour of metals (Durai et al, 2007). Rao et al (2009) studied the dry sliding wear behaviour of aluminium alloy and aluminium alloy - SiC composite using pin-on-disc apparatus against EN32
steel counter surface, giving emphasis on the parameters such as coefficient of friction, rise in temperature, wear and seizure resistance as a function of sliding distance and applied pressure. It was observed that the wear rate of the aluminium alloy was significantly higher than that of the aluminium alloy - SiC composite and is suppressed further due to the addition of silicon carbide particles. The overall results indicated that the aluminium alloy – silicon carbide particle composite could be considered as an excellent material where high strength and wear resistance were of prime importance.

Hosking et al (1982) reported that SiC particles were more effective than Al₂O₃ particles for the improvement of wear resistance of aluminium matrix composites due to high hardness. Gurcan and Baker (1995) and Lee et al (1992) also stated that the wear resistance of SiC reinforced composites are better than Al₂O₃ reinforced composites. Deuis et al. (1997) comprehensively reviewed the status of research in the area of dry sliding wear of discontinuously reinforced aluminium alloy MMCs. However, almost all the MMCs investigated had an aluminium alloy as the matrix material. It is known that particulate reinforcement strengthened and precipitated hardening act in a synergistic fashion (Rack, 1988). Increased content of SiC in iron – silicon carbide composites has resulted in significant improvement of both hardness and wear resistance (Ramesh and Srinivas, 2009).

Da Costa et al. (1999) evaluated the wear behaviour of aluminium matrix composites reinforced with Ni aluminides and showed that reinforcing aluminium alloys with intermetallics increased the wear behaviour highly. Kok (2006) fabricated Al₂O₃ particles reinforced aluminium alloy metal matrix composites by vortex method, and investigated in a pin on disc abrasion test. The wear resistance of the composites was considerably superior than the aluminium alloy and increased with increasing Al₂O₃ particles content and size.
Venkataraman and Sundararajan (2000) investigated the sliding friction and wear behaviour of aluminium alloy SiC particulate reinforced aluminium matrix composites under dry sliding wear conditions. Experimental observations indicated that there existed a strong correlation between the friction and wear of the mechanically mixed layers. Sharma et al (2006) investigated the influence of dispersed alumina particles on the wear behaviour of the aluminium composites in a corrosive environment. The composites were prepared by modified pressure die casting technique. The corrosive - erosive wear experiments were carried out on a proprietary corrosion - erosion wear tester to study the wear characteristics of the composites. From the results, it was noted that the wear rate varied marginally at low speeds but sharply increased at higher speeds. The corrosive wear rate logarithmically increased with the increasing concentration of the corrosive medium. Under the experimental conditions, the combined corrosion – erosion wear rate was found to be greater than that of the sum of the pure corrosion rate and pure wear rate was obtained from separate experiments. The corrosion behaviour of the composite specimens was dependent not only on the corrosion resistance but also considerably on their wear resistance. The corrosive - erosive wear rate decreased with increase in the reinforcement content in the specimens.

Rajnesh Tyagi (2005) investigated the friction and wear characteristics of Al - TiC composites under dry sliding using a pin-on-disc wear tester. The wear rate decreased linearly with increasing volume fraction of titanium carbide, and coefficient of friction also decreased linearly with increasing normal load and volume fraction of TiC. Shafaat Ahmed et al, (2007) found that the metal matrix composites were of great interest in recent years as they could offer a better combination of properties not attainable in conventional alloys. Al - based MMCs have been attracting a lot of attention particularly for their desirable combination of high stiffness and low specific gravity. Recently, tribological properties of Al - MMCs have also drawn much
interest. Rao et al. (2009) studied the dry sliding wear behaviour of aluminium alloy and aluminium alloy - SiC composite using pin-on-disc apparatus against EN32 steel counter surface, giving emphasis on the parameters such as coefficient of friction, rise in temperature, wear and seizure resistance as a function of sliding distance and applied pressure. It was observed that the wear rate of the aluminium alloy was significantly higher than that of the aluminium alloy - SiC composite and is suppressed further due to the addition of silicon carbide particles. The overall results indicated that the aluminium alloy - silicon carbide particle composite could be considered as an excellent material where high strength and wear resistance were of prime importance.

Increased contents of TiO$_2$ in Al6061 - TiO$_2$ composites resulted in higher hardness and lower wear coefficient. The wear coefficient decreased at higher loads and larger sliding distances (Ramesh et al, 2005). To improve the wear resistance of an aluminium alloy, an in-situ synthesized TiB$_2$ particulate reinforced metal matrix composite coating was formed on a 2024 aluminium alloy by laser cladding with a powder mixture of Fe-coated boron by Jiang Xu and Wenjin Liu (2005).

Al matrix reinforced with short plain steel fibres, copper-coated and nickel-coated steel fibres were fabricated by liquid process using vortex method. From the wear studies, it was found that addition of fibres reduced the wear rate considerably at all applied loads and the volumetric wear increased with increasing applied load (Mandal et al, 2004). Incorporation of carbon fibres into 2014 Al alloy significantly improved the wear resistance, served to suppress the transition to a severe wear rate regime and impeded the transition to a higher load in comparison to the unreinforced alloy. Also, the composite exhibited a higher seizure resistance compared to the unreinforced alloy (Daoud, 2004).
Sornakumar and Senthilkumar (2008) have developed the bronze-alumina composite by stir casting method. The flank wear of the carbide tools on machining bronze-alumina composite was higher than on machining bronze because of the abrasive characteristics of alumina. The surface roughness of machined bronze was lower than the surface roughness of machined bronze-alumina composite. Shorowordi et al (2004) developed two aluminium metal matrix composites reinforced with SiC/B\textsubscript{4}C particles made by stir casting followed by hot extrusion. From the pin-on-disc wear tests, it was observed that at higher sliding velocity lead to lower friction coefficient for both MMCs.

Genel et al (2003) carried out wear tests with pin-on-disc and the results showed that wear behaviour and the friction coefficient of the composites were significantly affected by the fibre volume fraction. More over, specific wear rate decreased with increasing fibre volume fraction and increased with increasing load and coefficients of friction of the composites were higher than that of the unreinforced matrix alloy. Sahin (2003b) investigated the wear behaviour of SiC\textsubscript{p} reinforced aluminium composite produced by the molten metal mixing method by means of a pin-on-disc type wear rig. Abrasive wear tests were carried out against SiC and Al\textsubscript{2}O\textsubscript{3} emery papers on a steel counterface at a fixed speed. The wear rate increased with increasing applied load, abrasive size and sliding distance for SiC emery paper, whereas the wear rate increased with applied load and abrasive particle, and it decreased with sliding distance for Al\textsubscript{2}O\textsubscript{3} emery paper. Sahin (2005) found that the abrasive grain size was the major parameter on abrasive wear, followed by reinforcement size.

The addition of reinforcing materials to the matrix significantly improved the composite wear resistance. However, the presence of particles of a very hard, ceramic phase of Al\textsubscript{2}O\textsubscript{3} and SiC increased the wear of the sliding
counterpart operating against the composite (Andrzej Posmyk, 2003). Yang (2003) carried out wear tests on three types of pins made of commercial A6061 aluminium alloy matrix composites reinforced with alumina particles. 10% alumina MMC was found to have higher wear coefficient values than those of 15% and 20% volume fraction of alumina particles. Due to the presence of a lower volume fraction of alumina in its matrix, the main wear mechanism of the worn pin surface confirmed adhesive wear. However, micro-cuts were found on the pin surface at distances of around 12 kilometre for MMC of 15% and 20% volume fraction of alumina particles caused by the dislodged alumina particles. Kestursatya et al (2003) conducted tribological tests with pins made from new lead free centrifugally cast copper alloy graphite metal matrix composite to a commonly used leaded copper alloy. The results showed that the graphite metal matrix composite had higher wear resistance than the leaded copper alloy.

Yılmaz and Buytoz (2001) studied the effects of volume fraction, $\text{Al}_2\text{O}_3$ particle size and effects of porosity in the composites on the abrasive wear resistance of compocasting Al alloy MMCs. From the results, the porosity in the composites depended upon the particle content, stirring speed, position and diameter of the stirrer. It is also identified that abrasive wear rates of composites decreased more rapidly with increase in volume fraction and size of $\text{Al}_2\text{O}_3$.

Ranganath et al (2001) fabricated the zinc / aluminium alloy composites reinforced with garnet particles by liquid metallurgy technique. The un lubricated sliding wear behaviour of zinc / aluminium alloy composites was evaluated by using pin-on-disc wear testing machine against steel disc. Results indicated that the wear rates of the composites were lower than that of the matrix alloy and further decreased with the increase in garnet content. However, in both un-reinforced alloy and reinforced composites, the wear rates
increased with increase in load and sliding speed. Increase in the applied load increased the wear severity by changing the wear mechanism from abrasion to particle cracking induced delamination wear. It was found that with the increase in garnet content, the wear resistance increased monotonically. The debris size was of the order of millimetres at higher load, while at the lower load, it was of the order of a few hundred micrometers.

Li and Tandon (2000) characterized the mechanically mixed layers and wear debris formed during sliding wear of an Al-Si alloy and an Al-Si/SiC<sub>p</sub> metal matrix composite against M2 tool steel under dry sliding conditions. They observed that the mixed layers and wear debris generated from the sliding systems had similar microstructural features and were comprised of a mixture of ultrafine grained structures, in which the constituents varied depending on the sliding loads.

Thiraviam et al (2008) identified that the wear resistance of composites increased with the increase of the reinforcement weight fraction due to the strong particulate matrix bonding and high hardness of the aluminium oxide particulates. Iwai et al (2000) investigated the wear behaviour of die-cast aluminium alloy composites reinforced with short alumina fibres using a pin-on-disc wear tester. Aluminium alloy reinforced with Al<sub>2</sub>O<sub>3</sub> fibres improved the dry sliding wear resistance.

Kassim S. Al-Rubaie et al (1999b) investigated the two-body abrasion tests on aluminium matrix composites reinforced with silicon carbide particles (SiC<sub>p</sub>). Wear analysis showed that SiC<sub>p</sub> reinforcement improved the abrasion resistance against all the abrasives used and increased with an increase in the volume fraction and size of SiC<sub>p</sub> reinforcement. Lim et al (1999) investigated the tribological properties of a group of aluminium alloy - based SiC particulate reinforced MMCs. From the pin on disc test, it resulted that the
rheo cast samples exhibited a better wear resistance at higher loads, when compared to MMCs having the same composition but fabricated using the powder metallurgy route. Kassim S. Al-Rubaie et al (1999a) investigated three body abrasion of aluminium matrix composites reinforced with silicon carbide particles and showed that SiC\textsubscript{p} reinforcement had increased the abrasion resistance against the abrasives used.

Sanjeev Das et al (2007) carried out a comparative study on abrasive wear behaviour of aluminium metal matrix composite reinforced with alumina and zircon sand particles. From that, abrasive wear resistance of both the composites improved with the decrease in particle size and also observed that the alumina particle reinforced composite showed relatively poor wear resistance compared to zircon reinforced composite.

Basavarajappa et al (2007) developed an aluminium metal matrix composite reinforced with SiC and graphite particles by liquid metallurgy route. Dry sliding wear behaviour of the composite was tested and compared with Al/SiC\textsubscript{p} composite based on Taguchi technique. Results showed that graphite particles were effective agents in increasing dry sliding wear resistance of Al/SiC\textsubscript{p} composites. Rosenberger et al (2009) determined the wear behaviour of alumina particulate reinforced aluminium matrix composites using a pin-on-ring machine against of a carbon steel ring and found that for the loads lower than 80N mild wear mechanism was present due to the formation of mechanically mixed layer; first hardening by mechanical alloying and strain hardening leads to an increase in thickness. At larger loads, the mechanisms were of a severe mode because of large instabilities which prevented the formation of a protective mechanically mixed layer.

Jiménez et al (2009) studied the tribological behaviour of mechanically alloyed aluminium base materials reinforced by NiAl\textsubscript{3} and found
that the addition of 1\% weight nickel slightly improved the wear resistance of mechanically alloyed aluminium, which possessed a homogeneous distribution of rounded NiAl\textsubscript{3} particles.

Harun Mindivan et al (2008) examined the tribological behaviour of squeeze cast aluminium alloy matrix SiC particle reinforced composites using a reciprocating wear tester by rubbing against an Al\textsubscript{2}O\textsubscript{3} ball on the composite surfaces in air and water. When compared to the sliding conditions during testing in air, the coefficient of friction and the wear rate of the composites were dramatically lower in water.

Adel Mahamood Hassan et al (2009) investigated the friction and wear behaviour of Al–Mg–Cu alloys and Al–Mg–Cu–based composites containing SiC particles using a pin-on-disc wear testing machine. The wear loss of the copper containing alloys was less than that of the copper free alloys and it was found that the silicon carbide particles played a significant role in improving wear resistance of the Al–Mg–Cu alloying system. The formation of mechanically mixed layer (MML) due to the transfer of Fe from counterface disk to the pin was observed in both Al–Mg–Cu alloys and Al–Mg–Cu/SiC composites. Kumar and Balasubramanian (2010) analysed the effect of reinforcement size, volume percentage of reinforcement, applied load, sliding speed and abrasive size on abrasive wear behaviour with a new mathematical model to predict the abrasive wear rate of aluminium alloy matrix composites reinforced with SiC particles.

Tribo - surface wear characteristics of two aluminium metal matrix composites with 13 \%vol. B\textsubscript{4}C and 13 \%vol SiC reinforcement were carried out using a pin on disc apparatus by Shorowordi et al (2006). It was found that wear rate of both Al-B\textsubscript{4}C and Al-SiC composites increased with increasing contact pressure which was accompanied by increased roughness of Al-MMC
tribo surface. The friction coefficient decreased slightly at high contact pressure. The wear rate and friction coefficient of Al–B₄C were lower than that of Al–SiC composite. Shaoyang Zhang and Fuping Wang (2007) investigated the friction and wear behaviour of the same brake materials dry sliding against two different brake drums made of aluminium matrix composite reinforced with different sizes of SiC particles (SiCₚ). It has been found that the brake material against the latter showed better friction performances and wear resistance than those against the former associated with small size SiCₚ pullout and thin tribofilm formation.

Sudarshan and Surappa (2008) fabricated aluminium alloy composites reinforced with fly ash particles. The dry sliding wear behaviour of unreinforced alloy and composites were studied using pin on disc machine. The dry sliding wear resistance of Al-fly ash composite was almost similar to that of Al₂O₃ and SiC reinforced Al-alloy. Composites exhibited better wear resistance compared to unreinforced alloy up to a load of 80N. Fly ash particle size and its volume fraction significantly affected the wear and friction properties of composites. Significant increase in the friction coefficient was observed when volume fraction of fly ash particles increased. Bekir Sadık Ünlü (2008) manufactured Al based Al₂O₃ and SiC particle reinforced composite materials by casting and powder metallurgy (PM) method and analized in the pin on disc wear test apparatus. The tribological properties of the particle reinforced Al composite specimens were improved and also mechanical properties of casting specimens were better than those of PM specimens.

Sheng-ming Zhou et al (2007) fabricated the aluminium composites embedded with Carbon Nano Tubes (CNTs) by pressure less infiltration process. From the pin on disc wear test investigation, the results indicated that the wear rate, friction coefficient of the composite decreased with increasing volume fraction of carbon nano tubes due to the self lubrication and unique
topological structure of CNTs content in the composite. Uyyuru et al (2006) studied the tribological behaviour of aluminium matrix composite / brake pad tribo-couple under dry sliding conditions using pin on disc machine. Chen and Breslin (2002) found that co-continuous alumina / aluminium composite materials with excellent physical and mechanical properties had offered great potentials for lightweight, wear resistant, and high temperature applications. Tjong et al (1999) have studied the wear behaviour of in situ aluminium - based composites by using a pin on disc test. The results showed that MMC prepared from the Ti-Al-B system had the highest volume wear due to the presence of large agglomerated TiB₂ particles which were ineffective in resisting shear deformation in the wear surface.

2.2.5 Literatures Related to Machining studies

There is a need for machining to achieve the desired dimension and surface finish. The metal cutting industries continue to suffer from a major drawback of not running the machine tools at their optimum operating conditions (Hari Singh and Pradeepkumar, 2005).

Metal Matrix Composites (MMCs) are extremely difficult to machine due to their extreme abrasive properties and the wear rate of the tools is also high, so that machining is extremely expensive. MMCs reinforcement particles are very hard and produce a quick increase in the tool wear rate due to the abrasion of the cutting edge. Till now, the usage of MMC and Al hypereutectic alloys in the automotive, railway and aerospace industries has been limited due to the high machining costs and short tool life. Poly Crystalline Diamond (PCD) toolings are not available for complex shape cutting tools. During the MMC parts machining, a SiC powder formation occurs with the coolant pollution, with a degradation of machine tool components and with a drastic decrease of PCD tool life (Durantea et al 1997).
Machining of MMCs has been difficult due to the extremely abrasive nature of the reinforcements and presents a significant challenge to the industry. A novel approach for predicting the wear rate during orthogonal machining of MMC was done by Kannan et al (2006). Pramanik et al (2008) investigated the effects of reinforcement particles on the machining of MMCs and found that the surface residual stresses on the machined MMCs were compressive and surface roughness was controlled by feed. The particle pullout influenced the roughness when feed was low, particles facilitate chip breaking and affected the generation of residual stresses, the shear and friction angles depended significantly on feed but were almost independent of speed.

During dry turning of SiC reinforced particulate, aluminium metal matrix composite tool wear was mainly affected by cutting speed and increased with increasing cutting speed (Kolckap et al, 2005). The failure of alumina particle’s interface, the debonded hard alumina particles or partly debonded alumina particles and scratch the tool rake face, leading to a high tool wear in alumina reinforced aluminium composite (Zhu and Kishawy, 2005). Manna and Bhattacharyya (2003) found that fixed rhombic tooling and fixed circular tooling were most effective for proper machining of Al/SiC MMC at high speed and low depth of cut, without build up edge or flank build up edge, which generally appears in conventional tooling system. Kevin Chou and Jie Liu (2005) investigated that the abrasive nature of the reinforced phase in MMC machinability was poor, tool wear was rapid, yet only diamond tools were technically suitable for MMC machining. Furthermore, diamond coatings seemed to be more economically viable than polycrystalline diamond for MMC machining.

Ramesh et al (2001) investigated a transient dynamic finite element analysis on the mechanics of diamond turning of an Al6061/SiCp metal matrix composite. From the analysis, they found when the tool was facing only the
aluminium matrix, the stresses nearer to the tool tip were predominantly tensile in nature for the observed stresses, but for the other cases, tensile stresses were found nearer to the tool tip, while compressive stresses were found a little away from the tool tip. It can be deduced that the position of the SiC element related to the tool motion generates different magnitudes and patterns in all the stresses. Kannan and Kishawy (2006) investigated the effect of cutting parameters and particulate properties (volume fraction and average particulate size) on the microhardness variations of the aluminium matrix beneath the machined surface. Lower reinforcement volume fraction and the coarser the particulates showed higher variations in microhardness.

Mariam et al (2004) developed a 3D thermo - mechanical finite element model of the machined composite workpiece to predict the effect of different cutting parameters on the workpiece subsurface damage produced due to machining and identified that high localized stresses in the matrix material around the SiC reinforcement particles leading to matrix cracking. Tonshoff (2000) highlighted the functional behaviour of machined parts was decisively influenced by the fine finishing process, which represents the last step in the process chain, and could as well be undertaken by cutting.

Lucchini et al (2003) have reported a tool wear mechanism in the turning of aluminium alloy reinforced with alumina using molybdenum toughened alumina tools. The results showed that the main mechanism of tool wear was abrasion and not heat. Scanning Electron Microscopic (SEM) examination revealed that molybdenum particles were easily torn from the matrix by flowing chips and molybdenum particles were not able to carry out their toughening action and they were responsible for the flank wear.

Yusuf Ozcatalbas (2003a) performed an experiment on machining of aluminium based metal matrix composite having in situ Al₄C₃ particles and observed that the hardness increased due to high volume fraction of Al₄C₃ in
the matrix. It resulted in a decrease in the formation of built-up edge but increased the surface quality at high cutting speeds. Yusuf Ozcatalbas (2003b) produced Al$_4$C$_3$ particles reinforced aluminium based composite by mechanical alloying. It was found that increasing the duration of mechanical alloying resulted in the formation of higher amounts of Al$_3$C$_4$ particles which therefore raised the hardness, but decreased the transverse rupture strength of the samples. During the machining of MMCs, due to the high volume fraction of Al$_4$C$_3$ in the matrix, decreased the formation of Built-Up Edge (BUE) and surface roughness at high cutting speeds. The effect of Al$_4$C$_3$ on the crack formation in shear plane reduced the cutting force, shortened the chip contact length and the chip segment thickness.

Caroline J.E. Andrewes et al (2000) machined with SiC reinforced aluminium metal matrix composite and results showed that initial flank wear on brazed polycrystalline diamond and chemical vapour deposition diamond coated tools were generated by abrasion due to the presence of very hard SiC particles. As machining progressed, thin films of the workpiece material were found to be adhering to the worn areas. Tool wear in these areas are combination of the abrasive and adhesive wear mechanisms. Quan et al (1999) have done experiments on SiC particle reinforced aluminium matrix composites and indicated that the chip deformation coefficient of composites decreased and the shear angle increased in comparison with those for the normal matrix aluminium alloy. There was an obvious difference between the two cutting processes of coarse particles reinforced composites and fine particles reinforced composites. In the latter, continuous chips predominantly formed and in the former continuous chips along and also debris were found.

Hooper et al (1999) machined the highly abrasive composite system of aluminium reinforced with silicon carbide particles and / or alumina fibres using polycrystalline diamond tools and indicated that polycrystalline diamond
tooling offered superior performance over carbide tools, both in wear resistance and the quality of the surface finish produced. The morphology of the wear scars on the tools were both adhesive wear and of the build up of defects. Kannan and Kishawy (2008) have done the machining of aluminium metal matrix composites and found that the wear mechanisms at lower cutting speeds and the lack of formation of a lubricating layer / film that could reduce the friction between the abrasive particle and the cutting tool. When turning at higher speeds, under wet conditions, the tool life was increased. However, the surface quality was deteriorated, due to the flushing away of the partially debonded particulates from the machined surface. Thus, higher percentage of pit holes and voids were formed.

Drilling is the most common process associated with the production of holes because of its simplicity, rapidity and economy. However, it is also one of the most complex cutting processes. The main feature that distinguishes it from other processes is the fact that cutting is combined with extrusion in the centre of the drill, at the chisel edge. Drilling is considered to be a complementary process of other more important processes, and yet 70% of the generated chip comes from this cutting technique. A typical machining process is comprised of drilling, turning, milling, threading and others. In the aeronautical industry, drilling is a very common machining process that takes place during all the manufacturing phases of aircraft construction. With regard to drilling, the aircraft industry is looking for improving the productivity and simplifying the automation of the riveting process. In order to achieve the above objectives, the aeronautical industry incorporates high speed machining techniques aimed at reducing cutting processing time, reduces or eliminates cutting fluids so as to avoid the need to clean structures before rivets are placed and to achieve high quality, burr free holes to eliminate the need to deburr before riveting (Rivero et al. 2006).
Gul Tosun and Mehtap Muratoglu (2004a) investigated experimentally type of drills, point angles of drills and ageing on the drilling performance of aluminium alloy reinforced with SiC particulates. The MMC was drilled in four heat treatment conditions: as-received, solution treated, and solution treated along with aged for 4h and 24h. Drilling tests were carried out using High Speed Steel (HSS), TiN coated HSS and solid carbide drills of 5 mm diameter and it was found that the effect of point angles on the sub-surface damage caused by the drilling operation was changed with the type of drills. Gul Tosun and Mehtap Muratoglu (2004b) conducted dry drilling tests at different spindle speed, feed rates, drills, point angles of drill and heat treatment, in order to investigate the effect of the various cutting parameters on the surface quality and the extent of the deformation of drilled surface due to drilling. From the experimental results, it was determined that increasing drill hardness and feed rate decreased the surface roughness of drilled surface for all heat treated conditions. The effect of point angles on the sub-surface damage caused by the drilling operation was changed with the type of drills.

Edith Morin et al (1995) drilled holes on the aluminium alloy as well as in a particle reinforced metal matrix composite consisting of SiC particles in an aluminium matrix with high speed steel drills of 10 mm diameter and measured thrust (normal force), torque and flank wear for several feed rates and drill speeds. From that, the flank wear became significant and proceeded linearly with depth of material drilled, or with the total distance passed by the lip or cutting edge of the drill. Ramulu et al (2002) conducted the drilling studies on Al₂O₃ aluminium based metal matrix composites by using different drills and found that Poly Crystalline Diamond (PCD) drills outperformed all other drills in terms of drilled hole quality, minimum drilling forces induced and lowest surface roughness parameters at the lowest feed rate with the highest cutting speed.
Emaa and Marui (2003) investigated the stability chart of chatter vibration occurring in drills for deep hole machining theoretically. Furthermore, suppression of the chatter vibration was attempted by using various drills with different point configurations and an impact damper. Xia and Mahdavian (2004) used single step drills to produce single step holes in steel. The performance of step drills was compared with that of conventional twist drills in the drilling of the free machining steel for the same task. The experimental results showed that for better cutting performance, the smaller diameter should not be less than 60% of the larger diameter and also the changes in the characteristics of the thrust force were influenced by the smaller drill of the step drill.

The flank wear of the carbide tools on machining bronze - alumina composite is higher than on machining bronze because of the abrasive characteristics of alumina (Sornakumar and Senthilkumar, 2008). Flank wear occurs on the relief face of the cutting tool and is generally attributed to the rubbing of the tool along the machined surface and high temperatures causing abrasive and/or adhesive wear, thus affecting tool materials properties as well as workpiece surface. Abrasion, diffusion and adhesion are the main wear mechanisms in flank wear (Senthilkumar et al. 2006a).

In the aerospace industry, depending upon the application, hole quality is very important (Basile, 1993). Haan et al. (1997) investigated the effects of cutting fluids on hole quality using a small diameter drill of less than 6 mm. Their study showed that dry drilled holes had a poorer surface finish than holes drilled with cutting fluid. Their second result was that dry drilled holes had a bell shape with the minimum diameter at the top of the hole. The effect of cutting fluids on the drilled hole surface was considerable. In dry drilling, the important factor for hole quality was thermal effects. The effect of thermal distortions on the diameter and cylindricity of dry drilled holes
indicated that thermal distortions of the drill and workpiece accounted only for a fraction of the total diametric errors (Bono and Ni, 2001).

Coldwell et al. (2004) assessed the machinability of aluminium alloy in terms of tool life, tool wear, cutting forces, chip morphology, hole diameter, cylindercity and out of roundness. Their study showed that high torque was correlated with high cylindercity values indicating problems with chip evacuation and hole size tended to decrease less than the drill diameter. Barnes et al. (1999) have shown that the height at the burrs produced during drilling was found to be greater with softer materials and the quality of the drilling surface was also inferior. The main wear mechanisms of HSS tools on drilling die cast magnesium alloy are adhesive wear; abrasive wear and diffusion wear (Wang et al. 2008).

Tool wear is a very important criterion for assessing the machining performance when machining with aluminium metal matrix composites. Flank wear occurs on the relief face of the cutting tool and is generally attributed to the rubbing of the tool along the machined surface and high temperatures causing abrasive and / or adhesive wear, thus affecting tool materials properties as well as workpiece surface. Abrasion, diffusion and adhesion are the main wear mechanisms in flank wear (Senthilkumar et al, 2006b). The flank wear rate determines the tool life during an end milling operation (Trent and Wright, 2000). Among the different forms of tool wear, flank wear is the significant measure as it affects the dimensional tolerance of the workpiece. The dimensional accuracy of the workpiece is controlled by flank wear of tools (Senthilkumar et al, 2003). The mean temperature in machining is proportional to the cutting speed and feed. The rise in temperature adversely affects the hardness and wear resistance of the cutting tool. Increased heat causes dimensional changes in the part being machined, making control of
dimensional accuracy difficult. The mean temperature in turning on machining is proportional to the cutting speed and feed (Kalpakjian, 1995).

The demand of low tolerances and better quality products have forced manufacturing industry to continuously progress in quality control and machining technologies. One of the fundamental metal cutting processes is end milling (Cevdet Gologlu and Nazim Sakarya, 2008). Milling is a machining process for generating machined surfaces by removing a predetermined amount of material progressively from the workpiece. The milling process employs relative motion between the workpiece and the rotating cutting tool to generate the required surfaces. In some applications, the workpiece is stationary and the cutting tool moves, while in others the cutting tool and the workpiece are moved in relation to each other and to the machine. A characteristic feature of the milling process is that each tooth of the cutting tool takes a portion of the stock in the form of small individual chips (Ronald A. Walsh, 2001).

The wide application of Computer Numeric Control (CNC) machine tools has significantly improved the machining efficiency and product quality in the metal cutting industry. The milling operation is one of the most useful and yet complex machining processes. In particular, the end milling process is commonly used for machining parts with complex surface geometries leading to variations in the depth and width of cut and hence the spindle loads. The machining parameters, such as the feed rate and spindle speed, are mostly selected by the programmers prior to the machining process. To avoid potential machine overload and tool failure, the programmers tend to use conservative feed rate and spindle speed (Ming Liang et al, 2002). High performance dry machining is one of the major trends in modern manufacturing. This advanced technology application results in a significant productivity increase, labour cost savings, as well as solving the environmental issues during the manufacturing process (Fox-Rabinovich et al, 2005).
High speed machining of aluminium alloy is growing both in terms of volume and performance, and the trend is likely to be maintained for the years to come. Aerospace and automotive industries are using high speed machining of aluminium to manufacture parts that represent only a fraction of the original aluminium alloy blocks volume. Due to high volume of material to be removed, increased productivity can be achieved only by increasing cutting speed and feed (Calatoru et al, 2008). Surface roughness is the relatively fine spaced irregularities on the surface of an object. The irregularity of a machined surface is the result of the machining process including the choice of tool, feed, speed and environmental conditions (SreeramaReddy et al, 2009). Sornakumar et al (1993) found that an ideal tool in turning is one which replicates its nose well on the work surface. The surface quality largely depends upon the stability of the cutting nose and the dimensional accuracy is controlled by flank wear of turning tools.

Serdar Karakas et al (2006) investigated the wear behaviour of various tools in milling process on Al- 4Cu / B₄Cₚ composites with constant feed rate and found that triple (TiCN +Al₂O₃ + TiN) coated tool exhibited highest wear resistance at all cutting speeds and also lower cutting speeds yielded lower tool wear.

High tool wear have been reported during conventional machining of the aluminium MMCs (Cronjäger, 1992). An alternative to effectively machine this material is to go for non-traditional machining techniques (Aronson, 1999). Electrical Discharge Machining (EDM) is one of the machining processes, which is widely used to produce intricate shapes on any conducting metal and alloy irrespective of their hardness and toughness (Lau et al, 1995). Frank Muller and John Monaghan (2001) proved that particle reinforced metal matrix composites were extremely difficult to machine using conventional manufacturing processes due to heavy tool wear caused by the presence of hard
ceramic reinforcement. They also investigated that the machinability of SiC particle reinforced aluminium alloy metal matrix composites using non-conventional machining such as EDM and laser cutting and found that EDM induced less thermal damage than using laser machining.

Metal Matrix Composites (MMCs) are well known for their superior mechanical properties over un-reinforced alloys. These composite materials are composed of a metallic base material called matrix, which is reinforced with ceramic fibre, whisker or particulates that impart a combination of properties not achievable in either of the constituents individually. A full scale application of these advanced materials however has been hindered due to their high cost of machining. They can be machined with either electroplated diamond grinding wheel or with carbide poly crystalline diamond cutting tools. In view of difficulties encountered, e.g. high tool wear and high tooling cost, during conventional machining, non-contact material removal processes such as the electric discharge machining offer an effective alternative (Sushant Dhar et al, 2007).

Electrical discharge machining is a non-traditional manufacturing process where the material is removed by a succession of electrical discharges, which occur between the electrode and the workpiece. These are submersed in a dielectric liquid such as kerosene or deionised water. The EDM process is widely used to machine hard metals and its alloys in the aerospace, automobile and mould industries. During the electrical discharge, a discharge channel is created where the temperature reaches approximately 12,000 °C, removing material by evaporation and melting from both the electrode and the workpiece. When the discharge ceases, there is a high cooling on the surface of the workpiece creating a zone affected by the heat that contains the white layer. Electrical discharge machining is governed by a thermal phenomenon therefore not only removes material from the workpiece but also changes the
metallurgical constituents in the zone affected by the heat (Jose Duarte Marafona and Arlindo Araujo, 2009).

Karthikeyan et al (1999) made an attempt to develop mathematical models for optimizing EDM characteristics such as the Metal Removal Rate (MRR), the Tool Wear Rate (TWR) and the surface roughness. The MRR was found to decrease with an increase in the percent volume of SiC, whereas the tool wear rate and the surface roughness increase with an increase in the volume of SiC. Ramulu et al (2001) investigated the effect of electrical discharge machining on the surface quality and subsequent performance of SiC particulate reinforced A356 aluminium under monotonic and fatigue loading condition. Narender Singh et al (2004a) had done an EDM experimental study on the effects of current, pulse on time and flushing pressure on responses like MRR, TWR, taper and surface roughness.

Rozenek et al (2001) investigated the effect of machining parameters (discharge current, pulse-on time, pulse-off time, voltage) on the machining feed rate and surface roughness during Wire Electrical Discharge Machining (WEDM) of metal matrix composite AlSi7Mg/SiC and AlSi7Mg/ Al_{2}O_{3}. Machining characteristics of WEDM metal matrix composites are similar to those which occur in the base material of AlSi7Mg aluminium alloy and machining feed rate of WEDM cutting composites significantly depends on the kind of reinforcement. Increase in cutting feed rate and surface roughness clearly follow the trend with increasing discharge energy as a result of increase of current and pulse-on time. Electrical conductivity and thermal conductivity of MMCs, are lower than those of the un-reinforced matrix alloy, which lead to decrease of material removal rate of EDM and WEDM.

Müller and Monaghan (2000) have done the machinability studies on SiC Particle Reinforced aluminium Metal Matrix Composites (PRMMC’s)
using non-conventional machining processes such as electric discharge machining, laser cutting and abrasive water jet. From the experiments, it was found that EDM was suitable for machining PRMMC’s with crater like surface and the size of the crater increased with increased discharge energy. Laser machining offered significant productivity advantages for rough cut-off applications with high feed rates. Reinforcing the aluminium matrix with SiC ceramic particles improved the machinability of the composite, due to the reduction in the optical reflectively of the material. The quality of the laser cut surface was relatively poor. Striation patterns on the cut surface, burrs at the exit of the laser and thermal induced microstructural changes were observed. Abrasive Water Jet machining (AWJ) was very suitable for rough cut applications without any thermal damage and no burr attachments on the composite, but the surface was relatively rough, and slotted-edge damage was observed on the top of the cut surface.

Che Chung Wang and Biing Hwa Yan (2000) had done the blind - hole drilling of Al₂O₃ / 6061Al composite using rotary electric discharging machining by using Taguchi methodology. Experimental results confirmed that the reversed copper electrode with an eccentric through hole had the optimum performance for machining from various aspects. Furthermore, either the polarity or the peak current most prominently affects the material removal rate, surface roughness or electrode wear rate amongst all of the parameters, whereas none of the non-electrical group has an equal affect.

Mohan et al (2004) investigated the machining characteristics of SiC / 6025Al composite using rotary electric discharge machining with a tube electrode. Brass was used as the electrode material to machine SiC / 6025Al composites and found that increase in volume percentage of SiC resulted in decrease in Material Removal Rate (MRR) and increase in Electrode Wear Rate (EWR). The decrease in the hole diameter and increase in speed of the
rotating tube electrode resulted in increase in MRR and decrease in EWR, and Surface Roughness (SR). In comparison, the electrode hole diameter and rotational speed had major effect on MRR, EWR and SR.

Narender Singh et al (2004b) have done the multi-response optimization of the process parameters viz., metal removal rate, tool wear rate, taper, radial overcut, and surface roughness on electric discharge machining of Al - 10 %SiC<sub>p</sub> as cast metal matrix composites using orthogonal array. Mohan Sen and Shan (2005) analysed the effects of applied voltage, capillary outside diameter, feed rate, electrolyte concentration and inlet electrolyte pressure on the productivity and the quality of small holes (<800 μm diameter) produced by using the electro jet drilling process.

The Standard Deviation (SD) indicates the dispersion of individual data values around their mean, and should be given any time we report data. Standard Error (SE) is an index of the variability of the means that will be expected if the study exactly replicates a large number of times. By itself, this measure doesn’t convey much useful information. Its main function is to help to construct 95% and 99% Confidence Intervals (CIs), which can supplement statistical significance testing and indicate the range within which the true mean or difference between means may be found. SDs, significance testing, and 95% or 99% CIs should be reported to help the reader. All are informative and complement, rather than replacing each other. Conducting our studies with these guidelines in mind may help us to maintain the standards in psychiatric research (David L Streiner, 1996 and Ronald E. Walpole et al, 2002).

2.3 RESEARCH GAP

There is a continuous improvement for high strength and weight reduction in all engineering materials especially in automobile and aerospace engineering applications. When the light alloy is reinforced with hard ceramic
particles, the strengthening of the matrix material is achieved. The mechanical properties of the metal alloy are improved by pressure die casting, but the development of metal matrix composites by the combination of vortex method and pressure die casting is rare. Based on the literature review, there are very few papers available on the development of metal matrix composites including aluminium / aluminium alloy - ceramic composites developed by the combination of vortex method and pressure die casting technique. Hence in the present work, new aluminium alloy - aluminium oxide / silicon carbide composites are developed by a new combination of vortex method and pressure die casting technique. Also, based on the literature review, there are very few papers are available on Tribological, Drilling, Milling and Electric Discharge Machining studies of metal matrix composites including aluminium / aluminium alloy - ceramic composites, developed by combination of vortex method and pressure die casting technique. Hence in the present work, Tribological, Drilling, Milling and Electric Discharge Machining studies have to be conducted on the newly developed aluminium alloy - aluminium oxide / silicon carbide composites to study their performance characteristics on processing for engineering applications. In this research work, it is proposed to identify a suitable mechanism with the objective of the development of new aluminium metal matrix composites and suitable machining processes for the aluminium metal matrix composites.

2.4 OBJECTIVES

After performing a detailed literature review, the following objectives are formulated for the present research work:

- Manufacturing of aluminium alloy based metal matrix composites with the combination of vortex method and pressure die casting technique. The aluminium alloy is reinforced with hard ceramic particle of aluminium oxide / silicon carbide.
• Machining of the aluminium metal matrix composites with HSS tools in drilling and milling processes.
• EDM studies of the aluminium metal matrix composites.
• Statistical analysis of all the experimental results to confirm the repeatability of the results.