CHAPTER 2

LITERATURE REVIEW

2.1 NEED FOR EVALUATION OF THE CAPABILITY OF ALUMINIUM ALLOY TO DEVELOP RESISTANCE TO WEAR

Aluminium matrix composites are attractive materials for structural applications in aircraft, automotive and military industries. High strength to weight ratio, environmental resistance, high stiffness and good wear resistance are the characteristics that encourage more researchers to develop their applications, with further improvement in the properties, particularly from the view point of their ability to resist wear. It is this property that lacks in them though they possess many other advantages making them good structural materials.

2.2 FACTORS INFLUENCING THE MECHANICAL AND TRIBOLOGICAL BEHAVIOUR OF ALUMINIUM METAL MATRIX COMPOSITES (AMCs)

2.2.1 Reinforcement Size and Shape

Several researchers have proved that the wear resistance of a material depends on its hardness, strength, ductility, toughness, the type of reinforcement used, volume fraction ($V_f$) and particle size (Das 1997, Das et al 2000, 2001, Lee et al 2002, Torrance 2002, Rodriguez et al 2007, Unlu 2008, Rohatgi et al 2010 and Chang et al 2010). Particle reinforcements have been proved to be the most effective in increasing the wear resistance of
MMCs (Modi et al 1992), given the fact that there exists a good interfacial bonding between the reinforcement and the matrix.

The subsurface deformation is eliminated, by preventing direct metal contacts which thereby increases the wear resistance of the composites (Zhang and Alpas 1993). Hard ceramic particles have been known to improve the wear resistance and resistance to seizure at extremely high temperatures. The addition of a reinforcement material results in higher hardness, superior elastic modulus, greater dynamic modulus, better damping capability and less coefficient of thermal expansion of the matrix alloy (Li and Chao 1996, Sahin 1998 and Muthukumarasamy and Seshan 1995). Increased abrasion (Kassim et al 1999) and sliding wear resistance and delayed transition from mild to severe wear are the effects of the addition of ceramic particles (Gurcan and Baker 1995 and Martin et al 1996).

It was noted that reinforcement particles with higher bonding strength with the matrix support the applied load better and prevent the initiation of cracks. This phenomenon helps to improve the wear resistance (Heguo Zhu et al 2008).

Zum Gahr (1979) studied the role of second phase particles that provided localized areas of high stress concentrations and also influenced the flow stress and wear rate. It was observed that the highest wear resistance was recorded in microstructures associated with fine, well-dispersed semi-coherent particles. For materials characterized by carbides, dispersed in a soft matrix, a decrease in the particle mean free path by reducing the carbide size resulted in improved wear resistance. The wear resistance of composites as compared to alloys was attributed to the favorable distribution of particles of a relatively small size (Vencl et al 2008).
The main issue regarding AMCs is that, the larger volume fraction and the finer size of the reinforcement particles make them even more expensive. Therefore, it is absolutely necessary to reduce the cost component by optimizing its volume fraction and avoiding/minimizing the use of finer particles (Uyyuru et al 2007). The reinforcement of fine Al₂O₃ particles strengthens the Al-matrix and increases the wear resistance (Das et al 2008). The residual alloy phase and the presence of a rigid ceramic skeleton enable the blunting or lubricating properties of the alloy in producing good tribological properties (Jayaram and Biswas 1999).

2.2.2 Effect of Different Types of Reinforcements

The SiC reinforcement in the AMCs is found to be more fracture resistant compared to Al₂O₃ and Si. The SiC particles are harder compared to other reinforcements and provide a very effective barrier to subsurface shear caused by the motion of the adjacent steel counterface (Kassim et al 1999, Wilson and Alpas 1996) and this result is likely due to the difference in particle shape (Garcia et al 1996). An additional drawback of AMCs with reinforcing phases, such as SiC and Al₂O₃, is the tendency of the reinforcement to act as a second-body abrasive against the counter-face, thus increasing its wear rates (Rang et al 1993). The reinforcement thus liberated as wear debris acts as a third-body abrasive to both surfaces. These effects are firstly, an increase in the wear rate for the system as a whole, when MMC is used compared to the monolith, which largely depends on the mechanical properties of the counterface material (Wang et al 2001).

Debris, like iron oxide, that is present in the wear track, plays an important role as it reduces the resistance to friction of MMCs reinforced with Al₂O₃ or SiC particles sliding against steel (Chen and Breslin 2002). The debris of mild wear mainly consisted of ferric oxide (Fe₂O₃), while the debris of severe wear was composed of Al₂O₃, Al, α-Fe phases. Moreover, the
addition of Si-Fe eutectic alloy and Al₂O₃ particles increased the transition load from mild to severe wear of Al 2024 alloy, by more than three times and also decreased the coefficient of friction (Korkut 2003).

The addition of TiO₂ particles resulted in the wear of the disc surface. The presence of these particles reduced both the plastic flow in the matrix as well as the metal transfer to the pin (Chaudhury et al 2005). Al 356 alloy reinforced with Ti-C was the hardest and exhibited the lowest wear rate and an increase in the load at which the transition from low wear rate to high wear rate occurs (Das 1997). Further, the addition of the graphite particulate to the AA 6061 caused a delay in the transition wear and also reduced the wear rate and coefficient of friction (Sharma 2001). The experimental results have shown a significant enhancement in the wear resistance of B₄C particle reinforced Al5083 MMCs (Yang 2007).

Composites that are cryogenically treated have shown considerable reduction in the wear rate, with an increase in hardness and strength at higher applied loads (Joel 2005). The MoSi₂ and Cr₃Si reinforced alloys (2124, 5056) exhibited the lowest specific wear rates (Walker et al 2005). The wear resistance of the composites showed improvement, with TiB₂ incorporated particle reinforcement and the refinement of the matrix grains, significantly improved the mechanical properties of the composites (Chaudhury et al 2005). Further, the TiB₂ particles markedly improve the wear performance of the Al–Cu alloy. It can be said that TiB₂ particles protect the matrix not only by virtue of their high hardness, but also by generating the fine iron rich debris, which acts as an effective lubricating medium (Mandal et al 2007).

2.2.2.1 EFFECT OF GRAPHITE

Generally, components made of aluminium alloy are light in weight and are widely used in common engineering applications. They lack
good resistance to wear under partial or boundary lubricating conditions. When a solid lubricant is dispersed in the aluminium alloy matrix, the material exhibits good potential for resistance to wear and consequently becomes more suitable for Tribological applications (Jha et al 1989). Efforts are being taken to incorporate lubricating particles in aluminium alloy matrices in order to improve its wear resistance properties. Prasad and Ramakrishnan (2009) had identified graphite as a suitable solid lubricating material for specific applications. Aluminium alloy/graphite particulate composites exhibit good resistance to wear delayed on-set of severe wear and seizure and better machinability.

Earlier researchers have shown that the aluminium alloy/graphite composite forms a layer of graphite with a solid lubricant between the contacting surfaces during dry sliding (Akhlaghi and Pelaseyyed 2004). These layers help in reducing the friction and wear and also postpone the onset of severe wear. A property of this layer is that, its thickness and hardness depend on the graphite content in the composite. Studies have also reported that with increasing graphite content, a richer graphite lubricating film is formed on the lubricating surface thus lowering the wear rate of the MMCs.

Gibson et al (1985, 1984), Jha et al (1989) and Das et al (1989) reported that, with the addition of a graphite particulate in the aluminium alloy, a solid lubricating film can be formed on the wearing surface. It helps to reduce the friction coefficient, to increase the anti-seizing quality and to improve the tribological behaviour of the base alloy.

Jha et al (1989) reported that, the porosity encountered in the Al/graphite composite during production, caused an embrittlement of the material with crack nucleation and elongation of the matrix alloy, leading to increased wear and reduction in fracture and toughness.
However, the addition of an appropriate level of the graphite particulate can reduce it. Also at increased sliding speeds the wear rate decreases, with the addition of the graphite content (Lin et al 1998). There are also reports indicating that with increased graphite content, the wear rate increases due to a reduction in the fracture toughness and hardness (Akhlaghi and Zare 2009). It is thus obvious, that for any aluminium alloy/graphite composite an optimum range of solid lubricant particulate content exists, at which the material exhibits the minimum wear rate and coefficient of friction.

2.2.2.2 INFLUENCE OF GRAPHITE ON HYBRID COMPOSITES

Aluminium based composites are being increasingly used in automobile, aerospace, marine and mineral processing industries, owing to their improved specific strength, good wear resistance, higher thermal conductivity and lower coefficient of thermal expansion. The widely used reinforced materials for this composite are silicon carbide (SiC), aluminium oxide (Al$_2$O$_3$) and graphite in the form of particles or whiskers. Aluminium based MMCs reinforced with ceramic particles, developed better mechanical properties than unreinforced aluminium alloys (Kimura 1993 and Raghumatham et al 1991) and are widely used for tribological parts, due to their high ratio of strength, stroke density and improved wear resistance (Shibata and Ushio 1994 and Chellman and Langenbeck 1993). This has been an incentive for the increasing attention towards particulate reinforced aluminium alloy composites for tribological applications (Banerj et al 1982 and Prasad et al 1986).

Kok and Ozdin (2007) investigated the effect of Al$_2$O$_3$ particle content and size on the wear behaviour of Al$_2$O$_3$ particle reinforced 2024 aluminium alloy composites fabricated by the vortex method. Surappa et al (1982) had studied the influence of 5 volume % Al$_2$O$_3$ particles’ addition on the wear resistance of hyper eutectic Al-Si alloys. Earlier, Straffelini et al
(1997) had studied the influence of the matrix hardness on dry the sliding wear behaviour of Al 6061/ Al$_2$O$_3$ composites; Szu et al (1997) had studied the effects of applied load and temperature on the dry sliding behaviour of Al 6061/ SiC composites; and Liang et al (1995) had identified that the MMCs containing SiC particles exhibit improved wear resistance. Reda et al (2008) and Clark et al (2005) had reported that pre-aging at various retrogation temperatures improves the hardness, tensile properties and electrical resistivity of Al 7075. Kim et al (2001) concluded that the hardness of aged Al 7075 alloy increases. Doel and Bowen (1996) had reported the improved tensile strength and lower ductility of Al 7075 reinforced with SiC particles. Komai et al (1993) had identified the superior mechanical properties of Al 7075 – SiC$_W$ composites.

A lubricant is added externally to reduce wear. This poses the problem that materials need periodic applications of lubricants, particularly to wear parts which are difficult to access. In such cases, self-lubricating materials are preferred because the solid lubricant contained in them can be automatically released during the wear process to reduce the wear. Graphite is one of the most widely used solid lubricant materials. In earlier studies, many authors had reported on the application of solid lubricants in aluminium composites, which contain small amount of graphite, that possess superior wear properties over the base alloy. The only limitation involved is that, using graphite as a solid lubricant cause loss of strength of the composite. To overcome the above problem, both ceramic and solid lubricants in a hybrid composite can improve the mechanical and tribological properties (Jun et al 2004, Tian et al 2006, Zhan and Zhang 2006, Rao et al 2009, Rao and Das 2010).

Du and Li (2004), Ahlatci et al (2006) studied the improvements on the wear properties of Al matrix by hybridization with Al$_2$O$_3$/ SiC composites and found that the wear resistance of the hybrid composites increases compared to the base alloy. Zhang et al (2006) found a higher wear
resistance in Al/ (Al$_2$O$_{3sf}$+SiC$_w$) hybrid composites than in Al/SiC$_w$ and Al/ Al$_2$O$_{3sf}$ composites.

2.2.2.3 B$_4$C AS THE REINFORCEMENT

Ceramic particles such as SiC, Al$_2$O$_3$, B$_4$C, TiC and TiB$_2$ are the widely used materials for the reinforcement of aluminium (Kaczmar et al 2000, Zhan and Zhang 2003, Tang et al 2008, Leng et al 2009, Hassan et al 2009, Mondal and Kumar 2009, Rahimian et al 2010, Ma and Lu 2011). Boron carbide (B$_4$C) is one of the most promising ceramic materials due to its high strength, low density (2.52g/cm$^3$), high hardness, good chemical stability and neutron absorption capability (Toptan et al 2010, Mohanty et al 2008 and Topcu et al 2009). B$_4$C can be used as an alternative to SiC and Al$_2$O$_3$, due to its high hardness for reinforcing AMCs, particularly for applications where good wear resistance is important. Aluminium/B$_4$C composites find their applications in nuclear industries, particularly because of the ability of the B10 isotope to capture neutrons (Thevenot 1990).

Al/ B$_4$C composites can be fabricated using different techniques, such as liquid phase methods (Shorowordi et al 2006, Lee et al 2001 and Lashgari et al 2010) and solid state consolidation (Powder metallurgy). Aluminium requires a temperature as high as 1100°C for wetting the B$_4$C surface completely (Lee et al 2002, Kerti and Toptan 2008). At such high temperature, the processing leads to the formation of undesirable compounds such as Al$_3$BC, AlB$_2$ and Al$_4$C$_3$ due to the chemical reactions between Al and B$_4$C.

These reaction products degrade the mechanical properties of the composites (Kouzeli and San 2002). A limitation involved in the production of MMCs is the chemical compatibility between the matrix and the reinforcement, especially in the liquid metal process. Casting MMCs is
an attractive process, because it is relatively inexpensive and provides a wide selection of materials and processing conditions. Al/ B₄C composites can be processed with low cost casting routes (Zhang et al 2007 and Shorowordi et al 2003). Below 1100°C, the wetting between Al-B₄C is poor and this poses a difficulty in the liquid phase. In order to overcome the difficulty and to improve their wettability and incorporation into aluminium melts, ceramics are generally heat treated or coated (Kennedy and Brampton 2001). Titanium is one of the reactive metals, which can be used to enhance the wettability in Al/B₄C systems (Halverson et al 1986).

In Al alloys, the bulk strength does not correlate with the wear and friction behaviour. Experimental observations indicate that there exists a correlation between the friction and wear and the transition behaviour (mild to severe wear) and the hardness, thickness and composition of the MML. The MML was present as long as the wear remained in the mild wear regime. The MML was absent in the severe wear regime. It can therefore, be concluded that the removal of MML or its non formation is responsible for the onset of severe wear.

In MMCs, the wear resistance is dependent on the kind of reinforcement and its volume fractions used. Initial severe wear is more effectively prevented by fibers and particles than whiskers. Particles are more beneficial for improving the wear resistance of the MMCs (Miyajima and Iwai 2003).

Composite materials reinforced with Al₂O₃ fibers and graphite, exhibited a homogeneous structure and were subjected to microscopic examination and hardness and wear resistance measurement. Hardness improvement was observed with the addition of Al₂O₃ fibers and graphite. Composites containing 10 % Al₂O₃ and 5 % graphite fibers were identified by the highest hardness of 112HV (Naplocha and Granat 2008).
Aluminium 6061 composites with Tungsten carbide (WC) and graphite particles (up to 4 wt. %) reinforcements, were successfully fabricated by the liquid metallurgy technique. An increase in the graphite content within the aluminium matrix results in an appreciable increase in the ductility, ultimate tensile strength, compressive strength and Young’s modulus, but a decrease in the hardness. Increasing the amount of the WC content in the matrix material resulted in an improvement in the mechanical properties, like hardness, tensile strength and compressive strength, with a reduction in the ductility. The highest values of the mechanical properties like hardness, tensile strength and compressive strength were noticed at 3 wt. % WC (Swamy et al 2011).

Discontinuously reinforced aluminium matrix composites have received increased attention, due to their high specific strength and stiffness, better wear resistance, improved high temperature properties and lower coefficient of thermal expansion over the conventional alloys (Ted 2000 and 2002, Kim et al 2001 and Ren et al 2008). The method of manufacturing plays an important role in deciding the properties and cost of these composites (William and Harrigan 1998, Onat et al 2007 and Seyed 2006). Metal matrix composites are generally produced by liquid metallurgy or powder metallurgy routes (Tjong and Tam 2006 and Ramesh et al 2010). The particles are mechanically dispersed in the liquid metal before casting and solidification through the liquid metallurgy route (Rosso 2006 and Seyed 2006). The drawbacks of the liquid metallurgy method are poor wettability of the reinforcing particles with the matrix alloy (Wan 2006, Gui and Kang 2001, Kerti and Toptan 2008 and Akhlaghi et al 2004), formation of inter metallic compounds, porosity at the ceramic/matrix interface (Akhlaghi et al 2004), formation of inter metallic compounds and an inhomogeneous distribution of the reinforcing particles in the matrix alloy (Wan 2006 and Gui
and kang 2001, Basavarajapa et al 2006). The conventional powder metallurgy methods involve the mixing of the matrix and reinforcement powders, compaction, sintering and secondary processes (Sivakumar et al 1998, Hrairi et al 2009 and Jha 1989). A relatively long mixing time is required for achieving a uniform distribution of ceramic particles within the aluminium powder. The development of new processing techniques for improving the properties of the composite materials has gained importance in recent years (Estrada et al 2009). The In situ Powder Metallurgy method (IPM) is a new processing technique for metal matrix composites (Akhlaghi and Pour 2010).

In this technique non-wetting ceramic particles are added to the molten alloy and the mixture is stirred in a specified time and temperature regime. The melt disintegration occurs by kinetic energy transfer from the stirrer to the metal, with the aid of the solid non wetting ceramic particles (SiC and Gr), to break up the liquid pool into droplets; after cooling in air, the resultant mixture of aluminium alloy and ceramic powder particles is consolidated to produce the final component.

The aluminium metal matrix composite is the combination of two or more constituents, in which one is the matrix and the other is the reinforcement. These materials are usually processed through the powder metallurgy or liquid casting routes. The powder metallurgy process has its own draw-backs, such as processing cost and size of the components. Therefore, the casting method is the optimum and economical route for processing of aluminium composite materials (Shivatsan et al 1991, Hashim et al 1999 and 2003).
The literature reports that most of the previous work was done on the use of SiC<sub>p</sub> as reinforcement in various aluminium matrix composites (Das 2004, Darell et al 2001, Rupa and Meenia 2005 and Daud et al 2004). However, much less information is available regarding Al<sub>2</sub>O<sub>3</sub> particulates reinforced in various aluminium matrixes (Ejiofor and Reddy 1997, Kook 2003, Surappa and Rohatgi 1981, Mohammad et al 2008).

The effects of SiC<sub>p</sub> in the aluminium with 4.5% Cu and 1.5% Mg, on the mechanical properties of materials were investigated by Stefanos (1996). He fabricated a composite material using the stir casting route and observed a positive response on fatigue and tensile strength in the heat treated condition, with the addition of SiC<sub>p</sub>. The stir cast aluminium alloy matrix and process parameters were thoroughly investigated by Pai et al (1993). They conclude that the stir casting process is simple and less expensive, compared to the other processing methods. They also claim that the properties of the cast composite material depend upon the uniformity of the dispersoids, wetting of the ceramic particles and low casting defects.

Balasivanandha (2006) investigated the stirring speed and stirring time on the distribution of ceramic particles in cast metal matrix composites, using SiC<sub>p</sub> reinforced in the A348 aluminium matrix. They recommended that 600 rpm stirring speed and 10 minutes stirring time gave the best results on the properties of cast aluminium composites.

Larger particles (71 micrometers) were generally homogeneous in the Aluminium 2024 matrix, while the smaller particles (29 micrometer) lead to agglomeration, segregation and porosities. The density of the composites decreased with increasing particle volume fraction and decreasing particle size; the porosity and the hardness of the composites increased with
increasing particle content and decreasing particle size. The abrasive wear properties of the 2024 aluminium alloy were considerably improved with the addition of the B₄C particles. The abrasive wear resistance of the composites was higher than that of the 2024 Al alloy. The abrasive resistance was due to the harder B₄C particles. Increasing the B₄C particle content and size caused an increase in the abrasive wear resistance of the composites (Canakci and Arslan 2012).

2.2.3 Effect of Reinforcement Volume Fraction

Researchers have reported that the wear resistance of the composites increased on increasing the volume fraction of the reinforcement (Lee et al 1992, Torrance 2002 and Das et al 2001). The wear resistance of the MMCs can be increased by as much as 70% by increasing the volume fraction of the reinforcing ceramic phase (Ceschini et al 1998). It was also found that the dry sliding wear resistance increases with an increase in the particle volume fraction. At a higher volume fraction, the friction coefficient was found to be higher and there was almost no effect of load on the friction coefficient (Uyyuru et al 2006).

The wear rates of the counter-face material increased with an increase in the volume fraction of the ceramic particles. This is mainly due to the fact that the hardness and strength of the composites are higher and they increased with an increase in the filler content (Das et al 2008). It was found that the volumetric wear rate increased with increasing applied load, while it decreased with increasing volume fraction of the filler material (Ferhat and Mehmet 2004). This may be due to the fact that the addition of ceramic particles caused a pronounced drop in the ductility (Nair et al 1985 and Ibrahim et al 1991), in addition to an increase in the hardness which may further increase the wear resistance of the composites. At any constant load, it was reported that the wear rate decreased with an increase in the addition of
SiC\textsubscript{p} and it also improved the load bearing properties of the Al-alloy during sliding. Increasing amounts of the addition of SiC restricted the flow or deformation of the matrix material with respect to the load (Kumar and Balasubramanian 2008).

In pure Al, the cumulative volume loss and the wear rate decrease linearly with increasing volume fraction of Titanium Carbide (TiC). The average value of the coefficient of friction also decreases linearly as a result of the protective cover provided by the transfer layer, with increasing volume fraction of TiC (Rajnesh 2005). The increase in the volume fraction of TiC caused an increase in the wear rate of the counterface. Therefore, it is suggested that when both the counter-face and composite wear are considered, an optimum volume fraction of particles exists at which the wear is the lowest (Shipway et al 1998).

### 2.2.4 Effect of Interfacial Bonding

The type of interfacial bonding between the Al-matrix and the reinforcement is an indication of the wear behaviour of the hard particle reinforced composite. This is due to the fact that the strong interfacial bond, which plays a critical role in transferring, loads from the matrix to the hard particles, results in less wear of the material. The mechanical properties of the composites containing hard ceramic particles are increased depends on the structure of the composites and good interface bonding (Deuis et al 1996). The improved interface strength better dispersion of the particles in the matrix can also be achieved by pre-heating the reinforcements (Sanjay et al 2001).

The nature of the surface of the reinforcement depends on the matrix composition, the nature of the surface of the reinforcement and the fabrication method of the composite (Ribes et al 1990). The interface offers site for crack nucleation and pull out the particle from the wear surface tending to higher wear loss due to poor interfacial bonding, (Prasad and Rothagi 1987). For example, Ni and Cu coated SiC dispersed Al-SiC
composites generally lead to good quality interfacial characteristics and exhibit improved wear properties (Sawla and Das 2004, Ramesh et al 2009).

The increase in elastic modulus and the strength of the composites are reasoned to the strong interface that transfer and distributes of load from the matrix to the reinforcement (Rang et al 1997).

2.2.5 Effect of Wettability

The wetting process avoids the use of an added solvent and mechanical mixing between the filler and matrix (Im and Kim 2011). The interfacial strength and wettability of the reinforcement in the matrix are related to one another. Better distribution of particles would help in achieving a decrease in the coefficient of friction and increase in the wear resistance, which is caused by the better wettability of the reinforcing phase with the matrix (Lloyd et al 1989). For example, reinforcement particles are sometimes coated for improving the wettability.

Based on work of the wetting of bulk ceramic (Levi and Kaplan 2002 and 2003), spreading of a liquid metal on a ceramic surface requires reaction between the liquid and the ceramic. Thus, only in cases where the liquid is reactive should spreading along the outer surface of the oxide layer. Indeed, aluminum in the present filler metal can serve as reactive element (Landry and Eustathopoulos 1996).

Aluminum cannot wet B₄C particles below 1000°C, so the contact angle to be reduced for B₄C particles at higher temperature (Danny et al 1989). At higher temperature aluminum will chemically react with B₄C particles and form undesired components.

2.2.6 Effect of Lubrication

Under lubricated conditions, the degree of direct contact between the surfaces is minimal and the wear progresses through the layers of debris (Bermudez et al 2001). For all materials, the wear loss in lubricated tests at
constant load decreases as the hardness increases. However, for lubricated conditions, Al-MMCs with higher hardness show higher wear resistance (Ma et al 1998).

The incorporation of solid lubricants would address problems such as scuffing and seizure; for instance, graphite in Al-Si alloys reinforced with SiC or Al₂O₃ particles (Gibson et al 1985). It was shown that the addition of graphite flakes or particles in Al-alloys increased the loads and velocities at which seizure took place under the boundary lubricated and dry sliding conditions (Das et al 1991, Das et al 1989, Rohatgi et al 1991, Ames and Alpas 1995). The high seizure resistance of the graphite in Al-matrix composites has been attributed to the formation of graphite layers on the contact surfaces, which act as solid lubricants, which reduce the metal-to-metal contact between the sliding pairs (Prasad and Rohatgi 1987, Rohatgi et al 1992, Rajaram et al 2011). One more important factor is that the lubricant used will act as a coolant between the two sliding surfaces, avoiding the consequences of increasing temperature of the metals in contact.

2.2.7 Effect of Load and Work Hardening

In an alloy, the rate of work hardening might be higher and there is every possibility of the entrapment of loose abrasives in the matrix, resulting in relatively reduced wear rate compared to the composite, with increasing load. For abrasive wear, the overall effect of the abrasive size on the wear rate becomes significantly less, compared to the contribution of the load, when the matrix of the composite is previously subjected to a particular amount of strain hardening effect, before being subjected to wear (Mondal et al 1998).

The lowering of the wear rate with respect to the sliding distance is a clear indication of more effectiveness of work-hardening at the subsurface regions due to increasing wear induced plastic deformation. Subsurface
hardening was characterized by increased hardness in the subsurface region as compared to the unaffected bulk (Modi et al 2001).

A work-hardening layer is formed on the wear surface during repeated dry sliding tests and this layer increases the wear resistance of the composites. The temperature at the wear surface also increases considerably. As a result of this phenomenon, recrystallization occurs on the worn surface during dry sliding, which causes a decrease in wear surface hardness and this significantly counter acts the promoting effect of the wear resistance caused by work hardening. In addition, the oxidization layer formed on the wear surface of the sample helps in improving the wear resistance (Heguo et al 2008).

2.2.8 Effect of Mechanical Mixed Layer (MML)

The specimen softens and becomes plastic during sliding at higher wear rates, due to the high temperature that is developed at the sliding surface. It reacts with the available oxygen and forms an oxide. The hard brittle oxide formed on the surface of the specimen gradually becomes thicker, continuous and covers the entire surface of the composite. It also acts as an insulator for thermal conduction. The MML thus caused a decrease in friction and wear rate of the MMCs (Ghazali et al 2005).

Another phenomenon causing an increase in the wear resistance of the composites is the transfer of steel inclusion from the counter face surfaces to the composite wear surfaces, which contributes to the increase in the wear resistance of the composites (Antoniou et al 1987). This indicates that the inclusion acts as an additional reinforcement at the wear surface of the composite and helps in load bearing (Wilson and Alpas 1996). The increase in the MML thickness results in a decrease of the specific wear rate. The MML formed on the worn surface of the matrix and composite, serves as a solid lubricant and acts as a protective layer (Uyyuru et al 2006 and Ferhat and Mehmet 2004).
The MML is stable for composites having low volume fraction under low loads and unstable at higher loads. In composites having higher a volume fraction of reinforcement, the MML is stable under high loads (Ravikiran and Surappa 1997). For various sliding loads, MMLs were formed on the worn surfaces. The mixed layers possessed micro-structural features, such as a mixture of ultrafine-grained structures, in which the constituents varied for different sliding loads (Li and Tandon 2000).

Venkataraman and Sundararajan (2000) reported that the thickness of the transfer layer increased under increasing load conditions. The wear rates of both the pin and disc are lower at higher speeds, due to the presence of the MML. With increasing speed the amount of layer formation increases, due to the higher temperatures generated. The extent of cover provided by this transfer layer is determined by the load, sliding speed and environmental conditions and it increases with increasing load because of the increased frictional heating and hence, better compaction (Ravikiran and Surappa 1997 and Tyagi et al 2002).

The MML provides surface protection before critical conditions are reached and the loose debris gets detached from the mixed layer, which is in agreement with the wear behaviour observations that at an intermediate load range, the wear rate was lower with the presence of the MML. The MML possessed a wavy shape in the cross section of the worn surface and was of non-uniform thickness across the entire wear track. Hence, the wear rate may be influenced by the formation and detachment of the MML in the particular load range used (Li and Tandon 2000).

In AMCs, the formation of the tribo-layer delays the transition from mild to severe wear. After the removal of the tribo-layer from the contact surface, the bulk material comes into direct contact with the counterface and therefore, it becomes difficult to form a new tribo-layer on the hot and softened matrix (Riahi and Alpas 2001). Due to further sliding, a drop in
the frictional force is noticed because the MML gets separated from the pin surface, caused by delamination which exposes the fresh pin surface (Prasada et al 2008). The results indicate that different types of reinforcement can generate MMLs. It can be concluded that the MML is formed from three sources; the counter-face, the matrix and the particles (Venkataraman and Sundararajan, 2000).

Certain characteristics that distinguish an MML from the normal composite are; (a) MMLs have a darker colour compared to the normal composite material when observed under an optical microscope. (b) The presence of chemical elements in the counter-face. (c) Higher micro-hardness value in the MML and a sudden change to lower values outside the MML (Rosenberger et al 2005).

The MML exhibited hardness values, which were much higher than that of the matrix in the composite (Riahi and Alpas 2001). The hardness of the MML is comparable to the hardness of the steel counterface and is independent of the composite. It is noted that, the MML is not formed in the non-reinforced material, which is evident due to the absence of traces of iron on the worn surface (Venkataraman and Sundararajan 2000). Micro-hardness studies conducted along the vertically sectioned surface beginning from the worn surface show that the magnitude of the hardness of the specimen decreases with the distance from the worn surface, which implies that the sub-surface nearer to the worn surface was hardened as a result of the strain hardening effect, compared to the region away from the worn surface.

Li and Tandon (1999) have reported that iron-rich oxidized tribo-layers were formed on the contact surfaces. The removal of these layers caused the transition from mild to severe wear regimes (Las and Rodriguez-Ibabe 2003). Almost all the investigations performed to date on the formation of tribo-layers and material transfer phenomena accompanying the sliding wear of Al-Si alloys, were conducted in an ambient atmosphere as a function
of the applied normal load and sliding speed. The SiC undergoes tribochemical interaction during sliding and forms SiO$_2$, which acts like a lubricant, especially at higher speeds (Ravikiran and Surappa 1997).

The increase in the volume fraction of TiC caused an increase in the protective cover provided by the MML. This phenomenon may be due to the higher hardness of the substrate that contains a higher amount of TiC, which is able to hold a thicker transfer layer of compacted oxide as compared to the substrate of lower hardness value (Saka et al 1977 and Tyagi et al 2002). When the reinforcement in the matrix has a wide size distribution, the wear rate and friction coefficients are found to be higher, compared to composite containing mono-size reinforcement (Uyyuru et al 2006).

### 2.2.9 Effect of Heat Treatment

After the heat treatment, the alloy and composites exhibit the minimum wear rate as the result of their improved hardness (Das et al 2008). In the case of a cast alloy, the value of the wear constant was higher than that of the heat treated alloy and composite. The cracks are mainly nucleated at the interface of the matrix and reinforcement, during the wear process. The heat-treated alloy and composite possess higher strength and hardness that caused fewer propensities for crack nucleation. They also showed an increase in the wear resistance (Vencl et al 2008). Due to the higher strength and ductility of the Al matrix, the effective stress applied on the composite surface during the wear process is less in the case of the heat treated alloys. This phenomenon caused a decrease in the cracking tendency of the composite surface as compared to the cast alloy (Sawla and Das 2004). The heat treatment did not radically change the morphology, but the hardening of the matrix by precipitation hardening took place, which led to higher hardness and strength (Vencl et al 2008).

The T6 thermal treatment condition was used to obtain the highest wear resistance. Studies indicate that the maximum hardening of the matrix
was obtained when the composite material was solutionized for 3 hours at temperature of 560°C, quenched at 0°C in ice water and aged at a temperature of 175°C for 7 hours. It is also reported that the T6 heat treatment for 7 hours provided the matrix great hardness and caused higher wear resistance in MMCs (Gomez and Barrena 2004). The higher hardness and yield strength of the composite by T6 heat treatment would have the advantage of preventing the formation of aluminium debris and decreasing its transfer to the surface of the steel (Singh et al 1999). The wear resistance of the under aged composites were found to be low when aged at low temperatures (between 50°-150°C). Increasing the ageing temperature to 200°C caused an increase in the hardness and abrasion resistance of the composites to the peak-aged condition.

The composites became over aged at 250°C and this caused a decrease in the wear resistance and hardness as a result of coarsening of the inter-metallic precipitates (Song et al 1995). Decreasing the Discontinuously Reinforced Aluminium (DRA) by under-aging and over-aging heat treatments, decreases the DRA wear rate under abrasive conditions by enhancing the creation of a protective solid film (Sannino and Rack 1996).

2.3 DRAWBACKS IN THE EXISTING LITERATURE

- Inadequate literature on the comparative study of AA6061 and the potential of AA 7075 to develop tribological properties with suitable particle reinforcement.
- Limited research literature is available for the current work on the tribological behaviour of AA 7075.
- Inadequate details on the dry sliding wear behaviour of AA 7075.
- Not enough material is available for identifying the tribological potential of AA 7075 under dry sliding conditions at room temperature.
2.4 OBJECTIVE OF THE STUDY

Though much research has been carried out in identifying the tribological potential of AA 6061 with different reinforcements, not enough work has been done on the tribological capability of AA 7075.

Hence, taking into account the need, the objectives of this work are,

- To identify the potential of AA 6061 for tribological applications reinforced with graphite and B_4C particulates.
- To study the mechanical properties of AA 7075 with reinforcements such as graphite, B_4C and Al_2O_3 particulates.
- To study the tribological behaviour and wear resistance properties of AA 7075 with the above reinforcements.

2.5 SUMMARY

Thus the literature survey indicates the suitability to study AA 6061 and AA 7075 with the right reinforcements, such as graphite, B_4C and Al_2O_3. While graphite is self lubricating material, ceramic like B_4C and Al_2O_3 have contributed, towards improvement in the mechanical properties and increase in the wear resistance.