TRIBOLOGICAL STUDIES ON ALUMINIUM SILICON ALLOYS AND ALUMINIUM SILICON CARBIDE COMPOSITE

A thesis submitted in partial fulfilment of the requirements for the degree of

Bachelor of technology
In

Metallurgical and Materials Engineering

By

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Department of Metallurgical and Materials Engineering
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NATIONAL INSTITUTE OF TECHNOLOGY ROURKELA

CERTIFICATE

This is to certify that the thesis entitled **"Tribological Studies on Al-SiC composite and Al-Si alloy"** submitted by Abhisek Panda (108MM003) and Prabhu Kalyan Mohapatra (108MM044) in partial fulfillment of the requirements for the award of BACHELOR OF TECHNOLOGY Degree in Metallurgical and Materials Engineering at the National Institute of Technology, Rourkela (Deemed University) is an authentic work carried out by him under my supervision and guidance.

To the best of my knowledge, the matter embodied in the thesis has not been submitted to any other University/ Institute for the award of any degree or diploma.

Date: 10th May, 2012

Prof. Dr. S.C. Mishra
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ABSTRACT

Among the materials of tribological importance, Aluminium-silicon composites have received extensive attention for practical as well as fundamental reasons. This investigation describes about the wear characteristics of Al-Si alloys and Al-SiC composite using particle erosion test and pin-on-disc wear test at room temperature. Here Si and SiC, having 10% and 5% (weight percentages) are taken with Aluminium by stir casting method. It is found that addition of silicon/ silicon carbide improves the wear resistance, machinability, and corrosion resistance. It has been found that the wear rate is strongly dependent on impact angle of erodent, impact pressure and velocity (in case of particle erosion); and applied load, sliding speed, alloy composition (in case of sliding wear). Erosion wear behavior is also been affected with the hardness. It is observed, Al-SiC particulate composite bears higher hardness than that of Al-10%Si alloy. Maximum erosion has taken place at 90° angle of impingement and the erosion amount is less with Al-SiCp than that of Al-10%Si alloy. From experiment it is conclude that Al-Si alloys and Al-SiC composite can use as a potential structural material.

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Chapter 1

Introduction

- Research Background
- Objectives of Research

Introduction

1.1 RESEARCH BACKGROUND

In recent decade, Aluminium-Silicon composites have potentially grown up in engineering structural applications ranging from automobile & aerospace industries to marine industries. Due to high strength to weight ratio, makes Al-Si composite a favorable material. Aluminum-Silicon alloys also constitute a important category among aluminum foundry alloys. Aluminum alloys with silicon, offers better corrosion resistance, excellent castability, good machinability property and easy weldability.

In different industries, materials exposed in high temperatures must be high resistant to hostile environmental effects/corrosion and similarly if the component is under heavy load, it must be resistant to deformation. It is usually possible to select a material/composite with suitable combination of properties [1]. Composite materials, which can be produced using a metallic matrix and fine ceramic particles, are recently being developed in order to protect the components in the elements of combustion chambers in diesel engines as they are subjected to high loading conditions, high temperatures and corrosive and erosive media [2-7].

One possibility to increase durability and performance of the materials for these applications is to protect them by using the composite coatings having a high degree of wear resistance. Such coatings can be economically produced by co-depositing metallic matrix together with fine and inert ceramic particles [8].

Aluminum-silicon eutectic phase is an anomalous eutectic process because it constitutes a metal (aluminum) and a non-metal (silicon). Aluminum-Silicon system is a simple binary eutectic with limited solubility of aluminum in silicon and limited solubility of silicon in aluminum. The solubility of silicon in aluminum reaches a maximum 1.5 at% at the eutectic temperature, and the solubility of silicon increases with temperature to 0.016% Si at 1190°C. The characteristic property of Aluminum-silicon is comparatively high tensile strength than that of other cast alloys such as ductile cast iron, cast steel etc. The high specific tensile strength of aluminum-silicon alloys is very strongly influenced by their composed polyphase microstructure.

The silicon content in standardized commercial cast aluminum-silicon alloys is in the range of 5 to 23 wt%. Some typical applications of aluminium silicon products are:

1. low-friction cylinder liners, crankcase etc. in automobile parts
2. In industry furnace (insert hole of thermometer etc.)
3. Thermal insulating material of heat and electrical equipment
4. Burner brick of industry furnace and furnace door, etc.

Aluminium-Siliconcarbide composite possesses a important role among Aluminium composite due to its High Thermal Conductivity, Isotropic Controlled Thermal Expansion, High Strength, Light Weight, High Stiffness etc. in different advance application, its demand gradually increases. Typical applications are high heat dissipation and spreading materials, Integration of cooling tubes-functional components, microprocessor lids/heat sinks, microwave housings, optoelectronic housings / bases etc.

In this investigation an effort has been made to understanding of the formation of the aluminum silicon composite both in unmodified and modified alloys and applying our understanding to alleviate the problems of wear in structural applications. This investigation described into different sections: 1) Background in which literatures are placed to explain Aluminum-silicon composite evolution; 2) experiments Procedures, which describes the detail plan, materials and procedures used in conducting the various experiments; 3) Results and Discussion describes the results found. Al-SiC composites have been prepared by addition of SiC powder in molten aluminium by stir-casting. Two type of Wear study have been done I.e. solid particle erosion wear test and abrasive wear test, which were done by Air Jet REG m/c and Pin on Disc machine respectively. For solid particle erosion, wear rate was calculated by measuring the cumulative mass loss. In abrasive wear testing, the wear rate was calculated in terms of wear depth by taking data from the DUUCOMP friction and wear monitor.

1.2 OBJECTIVES OF THE PRESENT PIECE OF INVESTIGATION

The objective of the present investigation is as follows:

- To determine the wear rate for solid particle erosion testing by calculating the cumulative mass loss for both Al-SiC composites and Al-Si alloys.
- To investigate the effect of operating parameter viz. impact angle, pressure on wear rate in solid particle erosion testing.
- To determine the wear and frictional force in abrasive wear testing for both Al-SiC and Al-Si.
- To study the effects of operating parameters viz. normal load, sliding speed and strand length on wear.

Chapter 2

Literature Survey

LITERATURE SURVEY

2.1 INTRODUCTION

The literature survey is carried out to study and evaluate the abrasive wear and solid particle erosion (SPE) wear properties of Al-Si alloys and Al-SiC composite. The various operating parameters viz. impact angle and applied pressure in solid particle erosion wear and normal load, sliding distance, sliding speed, silicon content for abrasive wear are studied . The work of researchers in this respect is been considered. Their conclusions are as follows:

M.M. Haque and A.sharif [9] have studied the wear behaviour of both as-cast and heat treated specimens were studied under dry sliding conditions at room temperature using a pin-on-disc type wear testing apparatus. The parameters for this test was sliding distance and load.

Wear increases with an increase in load and time is observed for both as-cast and heat treated specimens but for as-cast specimen wear is more pronounced.

For heat treated specimens a mild wear is observed at the wear surface, and for as-cast specimen an adhesive wear with plastic deformation is observed.

The overall investigation shows that the heat treated aluminium–silicon piston alloy has higher strength, hardness and wear resistance properties. However, in order to obtain best combination of the structure and properties in this material, further investigation is needed.

A.T. Alpas and J. Zhang[10] have studied The dry sliding wear behaviour of cast aluminium 7% silicon alloys (A356) reinforced with SiC particles was investigated by means of a block-on-ring (52100 bearing steel) type wear rig. Wear rates of the composites with 10–20 vol.% SiC were measured over a load range of 1–150 N at sliding velocities of 0.16 and 0.8 m s^{-1}. At low loads, corresponding to stresses lower than the particle fracture strength, SiC particles acted as load-bearing elements and their abrasive action on the steel counterface caused transfer of iron-rich layers onto the contact surfaces. In this regime, SiC reinforced composites exhibited wear rates about an order of magnitude lower than those of the unreinforced alloys in which wear occurred by subsurface crack nucleation, around the silicon particles, and growth.

Above a critical load determined by the size and volume fraction of SiC particles, carbide particles at the contact surfaces were fractured. A subsurface delamination process by the decohesion of SiC-matrix interfaces tended to control the wear, resulting in wear rates similar to those in the unreinforced matrix alloy.

An abrupt increase in the wear rates (by a factor of 102) occurred in the unreinforced aluminium-silicon alloy at 95 N. SiC reinforcement was proved to be effective in suppressing the transition to severe wear rate regime.

Dheerendra Kumar Dwivedi[11] has studied the effect of alloying elements on binary Al-17wt%Si alloy and multi-component (Al–17Si–0.8Ni–0.6Mg–1.2Cu–0.6Fe) cast alloy. A reduction in wear rate at high sliding speed was observed. This is due to the formation of an oxide layer on the sliding interface. Increase in the sliding speed leads to an increase in interface temperature. Rise in temperature increases the ability of soft Aluminium matrix to accommodate the hard and brittle Silicon. If temperature exceeds a certain critical value, thermal softening in the sub-surface region takes place which leads to large-scale plastic deformation.

Multi component alloys show better wear resistance because of increased solid solution strengthening, precipitation hardening and formation of intermetallic compounds in the presence of alloying elements. Formation of thermally stable intermetallic compounds and dispersion strengthening increase the wear resistance of multicomponent alloys. High hardness of these alloys is responsible for the low coefficient of friction during sliding due to easy fracture and deformation of asperities.

N. Axén ,M. Hutchings and S. Jacobson[12] studied and presented a model for the sliding friction of multiphase materials in abrasion. Different load distribution modes are used with Amontons' first law of friction to derive both the friction force and the coefficient of friction as functions of the area fractions of the phases, their individual coefficients of friction and their wear resistance. It is shown that the coefficient of friction of a multiphase material should depend on the load distribution mode and that the upper and lower limits for the coefficient of friction expected from composites or multiphase materials can be identified. For most pressure distribution modes, the friction depends on the wear resistance of the phases.

Y.Sahin [13] studied the wear behavior of aluminium composite reinforced with 10 wt% Al2O3 produced using powder metallurgy method. A comparison is made with SiC particle reinforced Alumium composite. The wear rate of both type composite increase with applied load but the wear rate is strongly dependent on normal load rather than type of particle used for manufacturing MMC.Plastic deformation was the dominant type of wear for Al2O3 reinforced composite where for SiC reinforced particle fragmented-deformed layer of particles was more effective.

Tuti Y. Alias and M.M. Haque[14] studied the wear behaviour of particle-reinforced MMCs and to develop regression equations for assessing the high stress abrasive wear rate of an aluminium–copper alloy–SiC–particle-reinforced composites vis-à-vis the matrix alloy as a function of the some variables like sliding distance, applied load and abrasive size. The wear rate of the matrix and composite materials increased with increasing abrasive size, applied load and sliding distance when the SiC abrasive paper was designed. However, the wear rate increased with increasing abrasive size and applied load, and decreased with increasing sliding distance when the Al2O3 emery paper was selected.

E. Candan , H. Ahlatci , H. Ç¨ımeno˘glu[15] studied the Abrasive wear behaviour of Al–SiC composites produced by pressure infiltration technique. The volume fraction of the SiC particles was 60% in the compacts. Abrasive wear tests were carried out under the normal load of 28 N, by rubbing the compacts to abrasive Al2O3 grains with diameters in the range of 85–250mm. Wear tests revealed that, the effect of the size of SiC particles on the wear resistance of compacts, depends on the size of the Al2O3 abrasive grains being rubbed. The compact which had 13mm SiC particles exhibited higher wear rate than the compact having 37mm SiC particles when rubbed on fine abrasive Al2O3 grains (<150mm). Wear tests performed on Al2O3 abrasive grains having diameters higher than 150mm revealed that, the compact reinforced with 37mm SiC particles had higher wear rate than the compact reinforced with 13mm SiC particles.

Aleksandar Vencl[16] studied the tribological properties of thixocasted and heat treated hypereutectic Al-Si alloy A-356. The samples consisted of two test specimens, the first of test specimens was made of thixocasted and heat-treated hypoeutectic Al-Si alloy A356 (EN AlSi7Mg0.3), ref. as Thixo T6. The second set of test specimens was made of grey cast iron (ref. as SL 26) with the following chemical composition (in wt. %): Fe-3.18C 2.17Si-0.60Mn- 0.7P-0.37Cr. Tribological tests were carried out on the pin-on-disc tribometer under dry and lubricated sliding conditions in ambient air at room temperature.

Obtained results of the tested materials mass loss, for different specific loads, were plotted as a function of sliding distance in the form of the comparative wear curves. The amount of worn material increased with increasing of the specific load. Almost from the beginning of the tests there was a steady-state wear in which the dependence of the mass loss from the sliding distance could be approximated as linear.

The wear rates (calculated for the steady-state period) of tested materials at different specific loads were calculated. With the increase of specific load the wear rate also increases for all materials. The coefficient of friction values did not change significantly with the change of specific load. The values of coefficient of friction were 0.32 and 0.53 for Thixo T6 and SL 26 material, respectively. The attained friction coefficient value of the grey cast iron was in expected range for metals in dry sliding conditions while the relatively low friction coefficient value of the Thixo T6 material is due to the fact that at applied specific load, pin surfaces of this material start to deform plastically and to flow.

The results of tribological tests under dry sliding conditions showed that the wear rates of the thixocasted and heat treated Al-Si alloy were almost two orders of magnitude higher than that of grey cast iron. Also, Al-Si alloy did not satisfy load bearing capacity criteria for the investigated load interval, and plastic flow of the material occurs. These results indicate that investigated Al-Si alloy has low adhesion wear resistance and could not be used for the same purposes, in dry sliding condition, as grey cast iron.

Tribological tests were also done in lubricating sliding conditions , where the parameters were normal load , sliding speed, lubricant type and temperature.

The obtained values of the coefficient of friction indicate that a boundary lubrication condition was maintained. for SL 26 material, the coefficient of friction decreases with the increase of sliding speeds, while, for Thixo T6 material, the coefficient of friction decreased up to the value of the sliding speed of app. 3 m/s, and than it starts to increase with the increase of sliding speed. Obtained results suggest that, from the aspect of friction in lubricated sliding condition, Thixo T6 material could be an adequate substitution for grey cast iron (SL 26) in cylinders of the piston machines.

S.A. Kori and T.M. Chandrashekharaiah[17] have studied the effect of grain refiner and/or modifier on the wear behaviour of hypoeutectic (Al–0.2, 2, 3, 4, 5 and 7Si) and eutectic (Al–12Si) alloys using a Pin-On-Disc machine under dry sliding sliding conditions.

Al-Si alloys solidify with fine equiaxed α-Al in hypoeutectic/fine primary Si particles in hypereutectic and fine eutectic Si. A fine grain size ensures good tribological properties. Al -Ti-B was used as grain refiner and Al-10%Sr was used as modifier.

Addition of grain refiner and modifier to Al-SI alloys resulted in less specific wear rate for these samples. Due to an increase in sliding speed , decrease of specific wear rate both in the case of grain refined/modified and grain unrefined/unmodified alloys was observed. This may be due to the fact that, at low sliding speeds, more time is available for the formation and growth of micro welds, which leads to increase in the force required to shear off the micro welds to maintain the relative motion, resulting in an increase in specific wear rate. Less specific wear rate was observed in grain refined/modified alloys under these conditions.

Addition of grain refiner and modifier led to decrease in wear rate at longer sliding distances. Grain refinement and modification led to increase in toughness and strength of the alloy. Increase in Silicon content leads to solid solution strengthening and precipitation hardening and a subsequent increase in the strength of the alloy. Addition of grain refiner and modifier leads to better mechanical properties.

G. Rajaram, S. Kumaran and T. Srinivas Rao[18] have studied the tensile and wear properties of Al-Si alloys fabricated by stir-casting technique at temperatures ranging from 250C to 3500C. It is observed that the wear rate decreases with increasing temperature. The reason might be the formation of an oxide film at high temperature which helps to avoid direct contact between alloy and the abrasive. Continuous sliding action removes this layer which facilitates direct contact of the alloy with the abrasive resulting in decrement of wear rate at high temperature (~3000C).

Another mechanism for this phenomenon has also been suggested. At elevated temperatures, the agglomerated clusters of oxide formed due to tearing of oxide layers are subjected to thermal stresses and compaction by applied pressure and high temperature. At the same time sintering of the wear debris is also occurring resulting in solid smooth hard surfaces called “glazes”. These glaze layers protect the sliding surface and reduce the wear rate.

H. Torabian, J.B Pathak and S.N Tiwari[19] have studied the effects of alloy composition, sliding distance, sliding speed and load on the wear rate of Al-Si alloys.

The wear rate depends strongly on the applied load. It increases linearly with load in three distinct regions in all the alloys; Mild wear , Intermediate wear and Severe wear. Mild wear takes a longer duration and takes place under low loads. The intermediate wear and severe wear regions are distinguished from the mild region by higher rates of increase in the wear rate per unit weight.

The transition load at which change take place from one region to another increases with increased Silicon content of the alloy. It is observed that wear rate initially decreases slightly with increasing sliding speed up to a certain value. Beyond this, there is a sharp rise in the wear rate, irrespective of the alloy composition. This value increases with increasing Silicon content.

The wear rate of the alloy is strongly dependent on the Silicon content of the alloy. The wear rate is found to decrease with increasing Silicon content. This effect is significant upto 15% Si in the alloy.Thus hypereutectic alloys exhibit better wear properties than hypoeutectic alloys.

Manoj Singla ,Lakhvir Singh and Vikas Chawla[20] have researched on the wear properties of Al-SiC composites which contained four different weight percentages 5%, 10%, 20% and 25% SiC. Friction and wear characteristics of Al–SiC composites were investigated under dry sliding conditions and compared with those observed in pure aluminium. Dry sliding wear tests have been carried out using pin-on-disk wear test rate normal loads of 5, 7, 9 and 11 Kgf and at constant sliding velocity of 1.0m/s.

It is observed that the volume loss increases linearly with increasing sliding distance. However the cumulative volume loss of composites is lower than that observed in pure Al and decreases with increasing volume fraction of SiC up to 20% and thereafter for 25% SiC wear loss again increases slightly & thus reverses the trend of decreasing wear volume loss with increase in SiC weight %. This trend is due to clustering of SiC particles and then due to increase in weight settling down at the bottom & non – uniform mixing in Al matrix.

On observation of variation of coefficient of friction with sliding distance, it was found out that friction coefficients fluctuate around the mean level and decreases as the sliding progresses. The fluctuations in the coefficient of friction may be due to variation in contact between sample and disk. Composites show lower coefficient of friction in comparison to pure aluminum. It is observed that average coefficient of friction decreases linearly with increasing load. Average value of coefficient of friction for pure Al is 0.6 & for composites decreases as the % SiC increases. Coefficient of friction for 25% SiC composite fluctuates between coefficient of friction for 5% & 10% SiC .

The scanning electron micrograph of worn surfaces of Al – 20% SiC composite reveals that a transfer layer of compacted wear debris is formed along with the wear tracks over the sliding surface. This layer reaches a critical thickness before being detached resulting eventually in generation of wear debris. The extent of cover provided by this transfer layer is determined by the load, sliding speed and it increases with increasing load because of the increased frictional heating and hence better compaction. The other reason for lower wear rate in composites is their high hardness as compared to pure aluminum resulting in lower real area of contact and therefore lower wear rate.

2.2TRIBOLOGY

The term Tribology was first used in 1966 in a report of the UK Department of Education and Science. The word Tribology is derived from the greek work tribos means rubbing. In a nutshell the meaning of Tribology is “science of rubbing” It the science and technology of interacting surfaces in relative motion and of related subjects and practices.. It includes parts of physics, chemistry, solid mechanics, Fuid mechanics, heat transfer, materials science, lubricant rheology, reliability and performance. The economic aspects of tribology are significant. Investigations by a number of countries arrived at figures of savings of 1.0% to 1.4% of the GNPs, obtainable by the application of tribological principles, often for proportionally minimal expenditure in Research and Development. The interactions taking place at the interface control its friction, wear and lubrication behavior. During these interactions, forces are transmitted, mechanical energy is converted, physical and chemical nature including surface topography of the interacting materials are altered. In many technological applications, the surfaces used are mostly either sliding or rolling.so understanding their Tribology is key to successful machine component design.Important parts of an automobile where study of its Tribology is vital are gear,brakes,clutches,cams,bearings,internal combustion engines etc.

2.3 METALMATRIX COMPOSITE

Composite material can be defined as a material consisting of two or more physically and chemically distinct parts, suitably arranged, having different properties respect to those of each constituent parts. Metal matrix are material where matrix is metal or its alloys. Metal matrix composites (MMCs) are types of material where varying the volume percentage of the reinforcement unique property combinations can be achieved. On the basis of reinforcement metal matrix composite can be classified into two groups.one continuous reinforcement composite where reinforcement is continuous fibres and the other one is discontinuous reinforced composite where reinforcement is used as particle, whiskers or short fibres. The common reinforcement used are silicon carbide, alumina, boron or graphite. Continuous reinforcement composite has advantages like:

1) lower coefficient of thermal expansion

2) improved wear resistance

3) higher thermal conductivity

Discontinuous reinforced composite have improved hardness, improved wear and fatigue resistance, dimensional stability and compression resistance. In recent engineering field MMC is a vast area of research.

2.3.1 Aluminium –silicon carbide metal matrix composite

Al-SiC has very low coefficient of thermal expansion which makes it compatible with direct IC device attachment for maximum heat dissipation for which it has wide application in advanced microelectronic packages.it has very low density .Besides it has very good Wear resistance properties. The following graph shows comparison of specific stiffness of SiC reinforced aluminium with other metals .

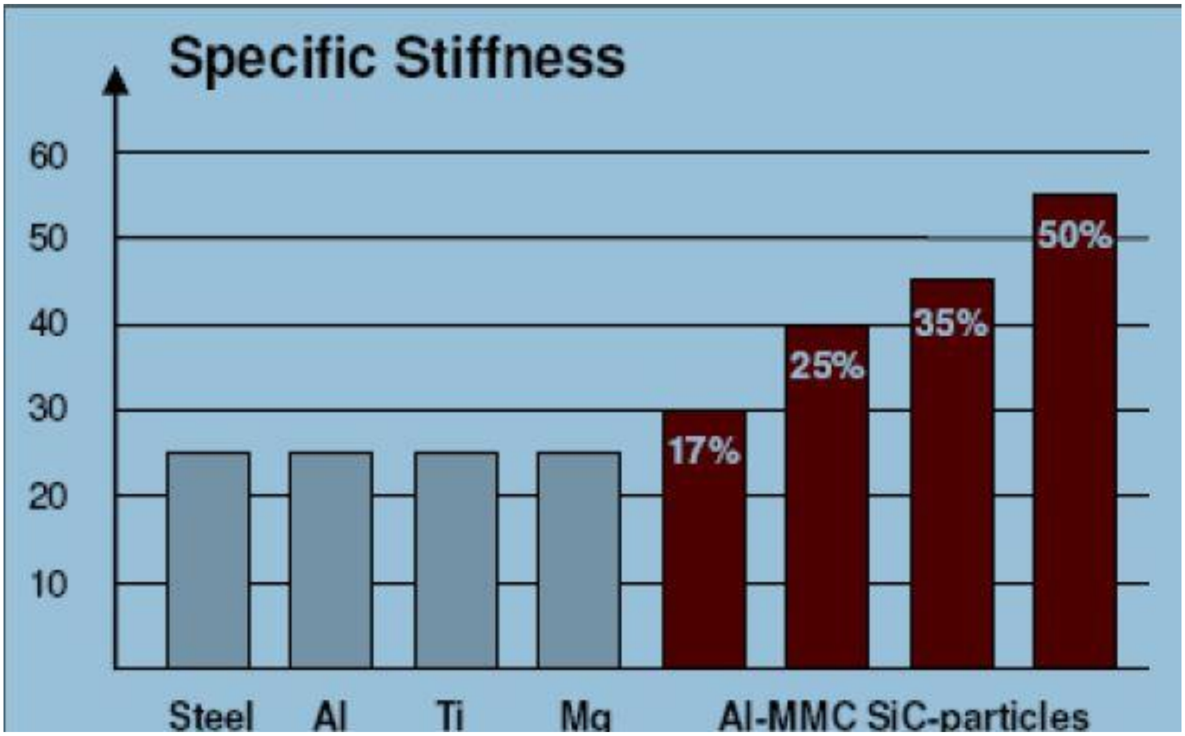

Fig 2.1.comparrision of specific stiffness of SiC reinforced composite with other metals.

The reinforcement types in the composites can be continuous, discontinuous, short, whiskers or particles since they have very high strength, stiffness and hardness. Attention has in general, been centred on the reinforcement of aluminium and its alloys. The application of SiC or Al_2O_3-reinforced aluminium alloy composites in aerospace and automotive industries has been gradually increased for pistons, cylinder heads, etc. However, much of the attention in wear studies has concentrated on the dry sliding wear behaviour of MMCs including various reinforcements such as SiCp, boron and Al_2O_3 particles. However, a limited number of researches on abrasion behaviour of ceramic particle reinforced aluminium alloy composites have been reported.

2.4 ALLOY

An alloy is a material that has metallic properties and is formed by combination of two or more chemical elements of which at least one is a metal.

The metallic atoms must dominate in its chemical composition and the metallic bond in its crystal structure. Commonly, alloys have different properties from those of the component elements. An alloy of a metal is made by combining it with one or more other metals or non-metals that often enhances its properties. For example, steel is stronger than iron which its primary element. The physical properties, such as density and conductivity, of an alloy may not differ greatly from those of its component elements, but engineering properties such as tensile strength and shear strength may be considerably different from those of the constituent material.

2.4.1ALUMINIUM ALLOYS

Aluminium alloys are alloys in which aluminium(Al) is the predominant metal. The typical alloying elements are copper, magnesium, manganese, silicon and zinc. There are two principal classifications, namely casting alloys and wrought alloys, both of which are further subdivided into the categories heat-treatable and non-heat-treatable. About 85% of aluminium is used for wrought products, for example rolled plate, foils and extrusions. Cast aluminium alloys yield cost effective products due to the low melting point, although they generally have lower tensile strengths than wrought alloys. The most important cast aluminium alloy system is Al-Si, where the high levels of silicon (4.0% to 13%) contribute to give good casting characteristics. Aluminium alloys are widely used in engineering structures and components where light weight or corrosion resistance is required. Aluminium alloys are mainly used in aerospace industry, marine industry, making cycling frames and other components, automotive industry etc. The prime reason for their wide application is their high strength to weight ratio as aluminium is a light metal. So designing auto parts with such alloys leads to less fuel consumption, stiffer and lighter designs can be achieved with aluminium alloys than is feasible with steels

2.4.1.1 ALUMINIUM SILICON ALLOYS

2.4.1.1.1 Aluminium-Silicon Eutectic and hypoeutectic alloys:

Alloys with Silicon as a major alloying element are by far the most important commercial casting alloys, primarily because of their superior casting characteristics in comparison to other alloys. A wide range of physical and mechanical properties is afforded by these alloys. Binary aluminium-silicon alloys combine the advantages of high corrosion resistance, good weldability, and low specific gravity. Although castings of these alloys are somewhat more difficult to machine than the aluminium-copper or aluminium-magnesium alloys, all types of machining operations are routinely accomplished, usually using Tungsten carbide tools and appropriate coolants and lubricants. Alloy 443 (5.3% Si) may be used for all casting processes for parts in which good ductility, good corrosion resistance, and pressure tightness are more important than strength. For die casting, alloys 413 and A 413 (12% Si) also have good corrosion resistance but are superior to alloy 443 in terms of castability and pressure tightness. Alloy A444 (7%Si-0.2% iron, maximum) also has good corrosion resistance and has especially high ductility when cast in permanent mold and heat treated to a T4 condition. This alloy has good impact resistance. Alloys 413, 443 and 444 are important binary aluminium-silicon alloys. Another group of aluminium-silicon alloys however represents the workhorse aluminium foundry alloys. In this group, silicon provides good casting characteristics and copper imparts moderately high strength and improved machinability, at the expense of somewhat reduced ductility and lower corrosion resistance. Alloy 319(6% Si -3.5% copper) is a preferred general purpose alloy for sand foundries that may also be used in permanent mold casting.

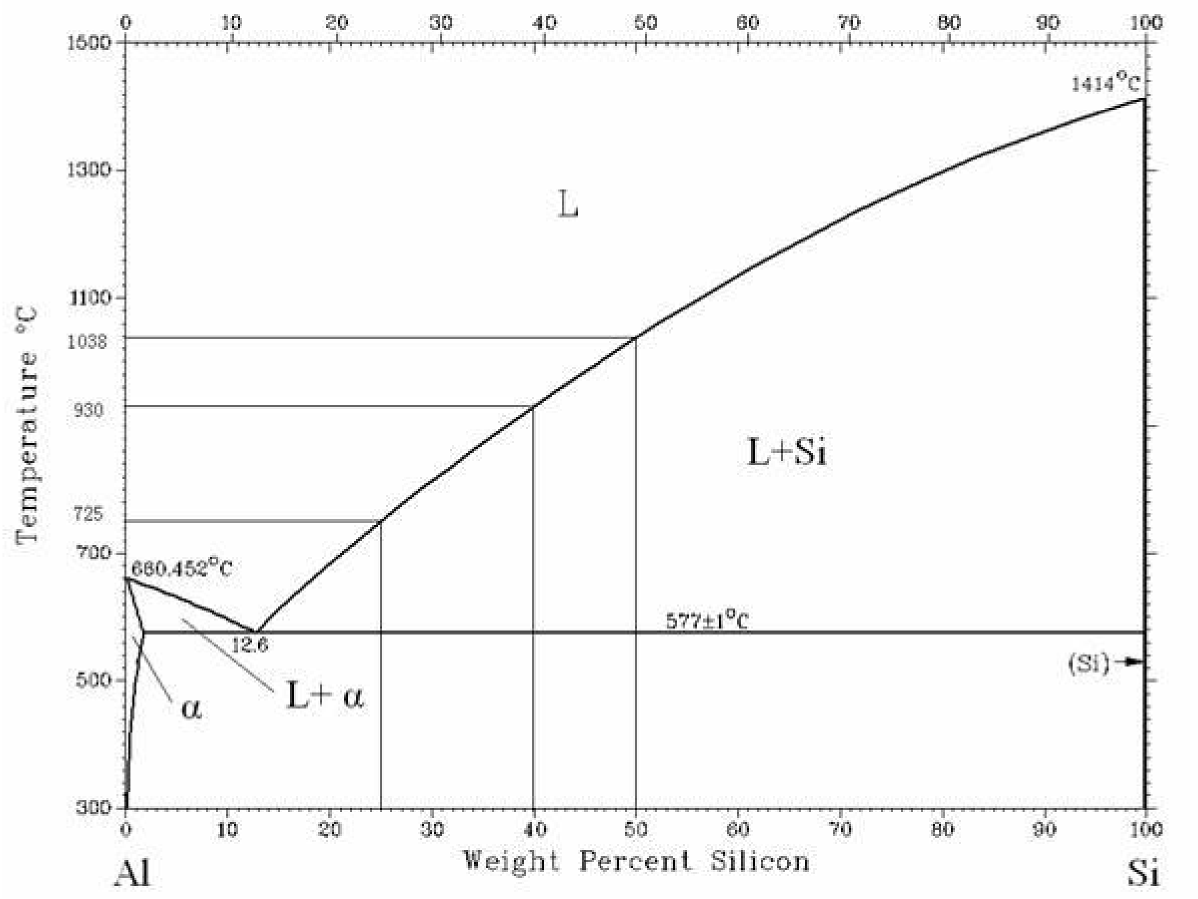

Figure 2.2 The Aluminium Silicon binary phase diagram. The eutectic occurs at 12.6 wt% Si.

2.4.1.1.2 Hypereutectic aluminium-silicon alloys:

Aluminum silicon alloys with greater than 12% Silicon are called hypereutectic aluminum-silicon alloys. These have outstanding wear resistance, a lower thermal expansion coefficient, and very good casting characteristics. Such alloys have limited use because the presence of the extremely hard primary Silicon phase reduces tool life during machining. Also the special foundry characteristics and requirements of this alloy system, needed to properly control microstructure and casting soundness, are not clearly as well understood as are the characteristics of conventional hypoeutectic alloys. These alloys have outstanding fluidity and excellent machinability in terms of surface finish and chip characteristics. A typical example is 390 alloy (17%silicon-4.5% copper-0.5% magnesium) whose outstanding wear characteristics have caused a rapid growth in its use. It is used in small engines, pistons for air conditioning compressors, master brake cylinders, and pumps and other components in automatic transmission.

2.5 WEAR

Wear can be defined as the progressive loss of material from one or both surface when two surfaces are in relative motion with each other.

2.5.1 TYPES OF WEAR:

(i) Single-phase wear: Single phase wear involves wear caused due to movement of a solid relative to a sliding surface. The relative motion for wear to occur may be sliding or rolling.

(ii) Multi-phase wear: In which wear, from a solid, liquid or gas acts as a carrier for a second phase that actually produces the wear.

2.6 WEAR MECHANISM

Classification of wear is a difficult task but knowing what type of wear helps in wear control. A great deal of experience is generally required to analyze surface topography created by wear, and to determine if wear is being produced by a chance encounter or by recurring contact.

Several types of wear can be found in machinery as:

(i) Abrasive wear

(ii) Solid particle erosion

(iii) Sliding and adhesive wear
(iv) Fretting wear
(v) Corrosive wear
(vi) Impact wear

2.6.1ABRASIVE WEAR:

It is the abrasive wear which occurs most frequently in machines. Abrasive wear is defined wear due to hard particles or hard protuberances forced against and moving along a

solid surface. There are no atomically flat engineering surfaces. The contacting surface touches at some high points only.so high stress develops at those points and it leads to localized plastic deformation. Abrasive wear is the removal of material by plowing, cutting, or scratching processes. However, since the surfaces are moving tangentially, this deformation results in microscopic grooves. Main cause of Abrasive wear can be by hard particles caught between sliding surfaces or by dragging metal parts over soil, concrete, or other rough areas. Abrasive wear also occurs under lubricated conditions – especially during boundary lubrication.

2.6.1.1MECHANISMS PROPOSED

Many mechanisms have been proposed to explain how material removal during abrasion.

These mechanisms include fracture, fatigue, and melting. Due to the complexity of abrasion process, no single mechanism completely accounts for all the loss. If there are only two rubbing parts involved in the friction process the wear is called two body wear. If the wear is caused by a hard particle (grit) trapped between the rubbing surfaces it is called three body wear. The particle may be either free or partially embedded into one of the mating materials. According to the recent tribological survey, abrasive wear is responsible for the largest amount of material loss in industrial practice [25].

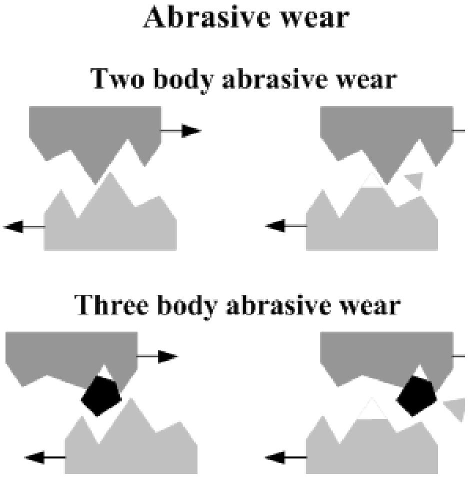

Fig 2.3 Abrassive wear process

2.6.2 SOLID PARTICLE EROSION (SPE)

SOLID-particle erosion is a loss of material during repetitive impacts of solid particles. A description of the erosion mechanism in terms the mechanical properties was presented by Bitter. when the yield strength of the material is exceeded, plastic deformation takes place in the vicinity of the impact. After multiple impacts, a plastically deformed surface layer may form near the eroded surface, and, therefore , the yield strength of the material increases due to strain hardening. Upon further deformation, the yield strength at the surface of the material will eventually become equal to its fracture strength, and no further plastic deformation occur. At this point, the material surface becomes brittle and its fragments may be removed by the subsequent impacts. Some researchers have suggested that, during erosion, mate rial loss from a metal surface occurs when a critical fracture strain is achieved at the surface. A critical fracture strain may be achieved locally after single or multiple impacts by the erodent particles. As material is lost at the attainment of the critical strain, the material below the surface is still

plastically yielding. in order to design a material to resist erosion, attention must be given to providing a microstructure that, ideally, never accumulates critical fracture strain. Hardness is the most widely used material property to correlate with the erosion rates of material. However the effect of hardness on material property is strongly dependent on erosion test conditions and nature of eroding particles. The important operating parameters which affects the erosion wear rate is angle. Between erosion rate and impact angle, the relationship is established by Lishizhou is as follows:

$$E = A\cos^{2}\alpha \sin (m\alpha) + B \sin^{2}\alpha \text{ ------(1)}$$

For typical brittle material, *A* is equal to zero and the erosion rate is largest at 90^{o} impact angle. For typical plastic material, *B* is equal to zero and the erosion rate is largest at about 20^{o}–30^{o} impact angle. Further, it is also observed that the mass loss and thus in turn the erosion wear rate is higher in case of SiC erodent than that of dry silica sand of same particle size. It may be due to higher hardness of SiC as compared to dry silica sand. Studies on effect of erodent hardness on erosion rate also suggest an increase of erosion rate with increase in hardness of the impinging particle.

2.6.3ADHESIVE WEAR

Adhesion wear is a result of micro-junctions caused by welding between the opposing asperities on the rubbing surfaces of the counterbodies. The load applied to the contacting asperities is so high that they deform and adhere to each other forming micro-joints. The motion of the rubbing counterbodies result in rupture of the micro-joints. The welded asperity ruptures in the non-deformed (non-cold worked) regions. Thus some of the material is transferred by its counterbody. This effect is called scuffing or galling.

When a considerable areas of the rubbing surfaces are joined during the friction a Seizure resistance (compatibility) seizure of one of the bodies by the counterbody may occur.

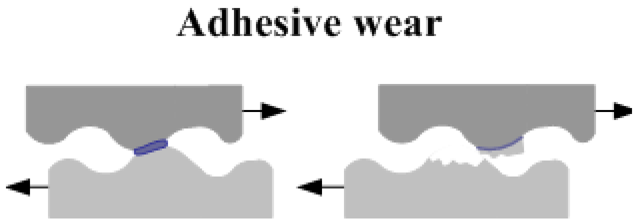

Fig 2.4 Adhesive wear process.

2.6.4 FRETTING WEAR

Fatigue wear of a material is caused by a cycling loading during friction. Fatigue occurs if the applied load is higher than the fatigue strength of the material. Fatigue cracks start at the material surface and spread to the subsurface regions. The cracks may connect to each other resulting in separation and delamination of the material pieces.

One of the types of fatigue wear is fretting wear caused by cycling sliding of two surfaces across each other with a small amplitude (oscillating). The friction force produces alternating compression-tension stresses, which result in surface fatigue. Fatigue of overlay of an engine bearing may result in the propagation of the cracks up to the intermediate layer and total removal of the overlay.

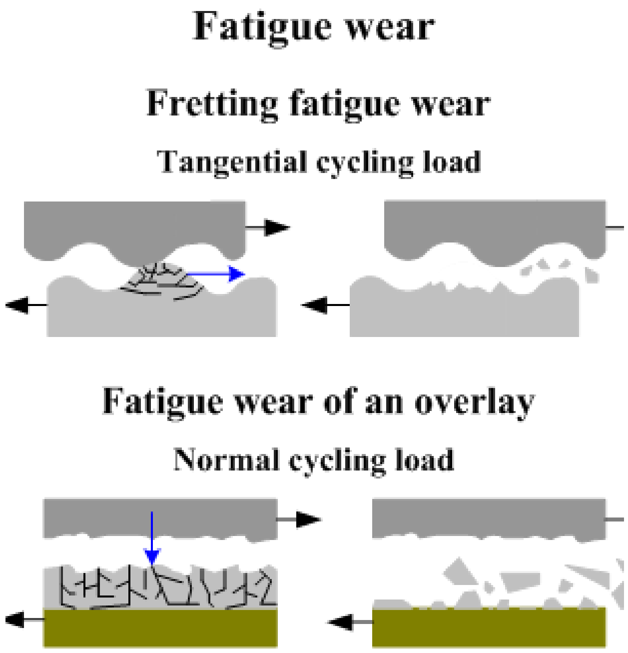

Fig 2.5 Freeting wear process

2.7 SYMPTOMS OF WEAR

Wear is a characteristic of the system & its surrounding and is influenced by many parameters. So it is necessary to understand the wear mechanism to protect the metal. In Laboratory scale investigations, individuals of tribo-systems are carefully control and study the effects of different variables on the wear behaviour of the coating. The data generated through such research under controlled conditions may help in correct interpretation of the results. A summary of the appearance and symptoms of different wear mechanism is indicated in Table 2.3[21] and the same is a systematic approach to diagnose the wear mechanisms

Table 2.1 Different wear mechanism, symptoms and surface appearance

Type of wear	Symptoms	Appearance of worn out surface
Abrasive	Presence of chip-out of surface	Grooves
Adhesive	Metal transfer s prime symptoms	Seizure, catering rough and torn-out surfaces
Erosion	Presence of abrasives in the fast moving fluid and short abrasion furrows	Waves & Troughs
Fatigue	Presence of surface or subsurface cracks accompanied by pits and spalls	Sharp and angular edges around pits
Corrosion	Presence of metal corrosion products	Rough pits and depressions
Delamination	Presence of subsurface cracks parallel to the surface with semi-dislodge or loose flakes	Loose, long and thin sheet like particle
Impacts	Surface fatigue, small sub-micron particles or formation of spalls	Fragmentation, peeling and pitting
Fretting	Production of voluminous amount of loose debris	Roughening, seizure and development of oxide ridges
Electric attack	Presence of micro-craters or a track with evidence of smooth molten metal	Smooth holes

2.8 RECENT TRENDS IN MATERIAL WEAR RESEARCH

Most of wear researches carried out in the 1940's and 1950's were conducted by metallurgical and mechanical engineers to generate data for the protective structural materials of different motor drive, trains, bearings, brakes, bushings and other types of moving mechanical assemblies [22]. It became apparent during the survey that wear of metals was a prominent topic in a large number of the responses regarding some future priorities for research in tribology. Much of the wear research conducted over more than past 50 years is in ceramics, polymers, composite materials and coatings [23]. Now-a-days this type of researches is in rapid progress in different country in different part of the world.

CHAPTER 3

EXPERIMENTAL DETAILS

EXPERIMENTAL DETAILS

3.1Sample preparation

Materials used for testing are :

1)AlSiC metal matrix composite(5% SiC reinforcement)

2)Al-Si alloys(10% Si)

Tests Carried out for each sample:

1)Particle erosion wear test

2)Sliding wear test using Pin on disc machine with DUUCOMP monitor

Total number of samples prepared:Total 4 samples are preapared.2 samples from AlSiC composite and 2 samples from Al-Si alloys.one for particle erosion test and one for sliding wear test for each of the material.

AlSiC metal matrix composite is produced by stir casting route.Molten aluminium metal is poured into a crucible and SiC powder are incorporated into the mould. Stirring is done by mechanical means and they are allowed to solidify. sample of dimension is machined from the as-cast sample for erosion wear test. cylindrical samples of 12mm diameter and 15mm height are machined from the as-cast Al-SiC ingot in the lathe machine for sliding wear test .Test samples were obtained from those cylindrical pieces by polishing them.

Molten Al-Si alloy is poured in to a crucible and allowed to solidify.A sample of 4cm*3cm*1cm dimension is machined from the as-cast alloy using a Hexer for erosion wear test.A cylindrical sample of 12mm diameter is machined from the as-cast alloy for sliding wear test.Surface are polished prior to testing.

3.2SOLID PARTICLE EROSION WEAR TEST:

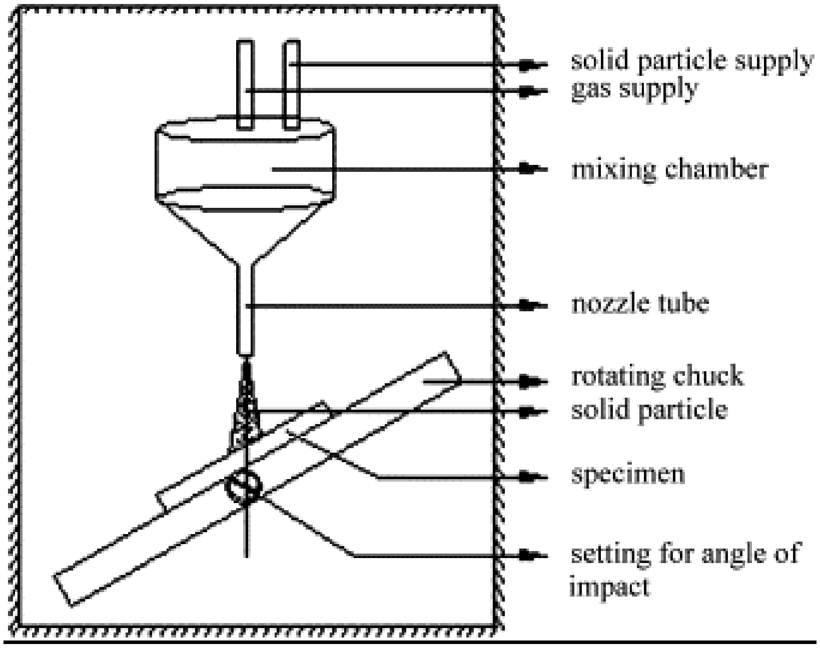

Fig 3.1 Erosion wear test apparatus.

The solid particle erosion (SPE) test system involves repeated impacts erosion by pressurized air driving the potential energy of the erodent particles striking the surface of the test sample. The amount of mass

loss of the tested sample divided by the mass of erodent can present the wear rate, or the volume loss can be also evaluated to rank the erosion resistance of full range of materials, ceramics, metals, coatings,

thin films and composites. The impingement angles can vary from 15° to 90° assisted by a flexible holder. The erodent particles are typically a mixture of Al2O3 particle and sand particles. Pressure is controlled using a compressor.

Table 3.1 Specifications of erosion wear test apparatus

Feed rate of erodent particles	-
Stand-off distance	10cm
Nuzzle diameter:	-
Pressure	up to 5 bar
Standard sample dimension	40x40x5-10 mm

Incident impingement angle	up to 90°
Temperature (surface)	up to 250° C

Table 3.2 specifications of Air jet REG apparatus.

3.2.1WEAR PARAMETERS

The variables involved in solid particles erosion wear tests are:

- Incident angle
- Gas Pressure
- Time of impact

  The effect of each parameter on wear is studied individually in this experiment.

3.2.2WEAR MEASUREMENT

Erosion wear rate can be calculated using the following formula:

Er=ΔW/We

Where Δw=change in weight of the specimen due to bombardment with eroding particle.

W(e)=weight of the eroding particles strike at time.

3.3SLIDING WEAR TEST APPARATUS

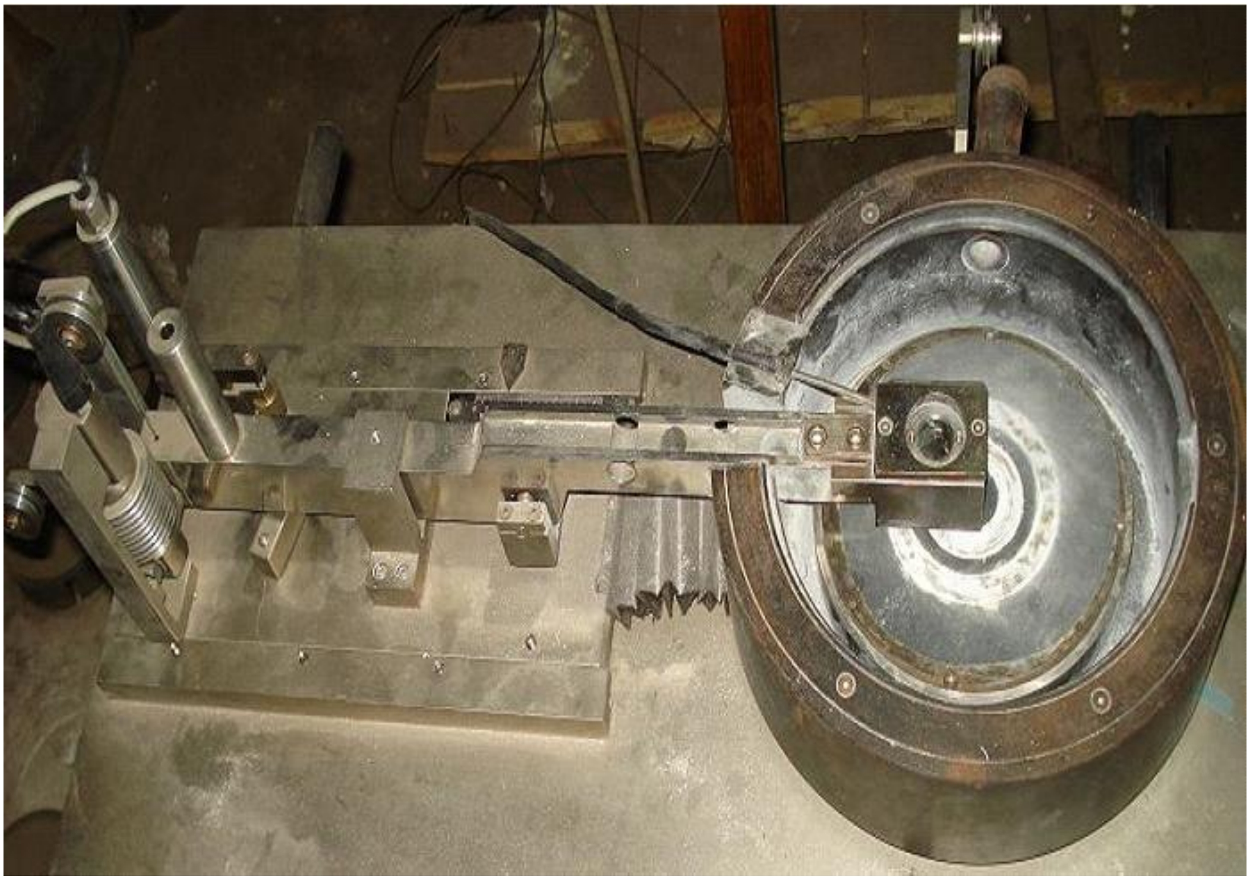

Fig 3.2DUCOM WEAR AND FRICTION MONITOR

DUCOM WEAR AND FRICTION MONITOR

The machine consists of a pin on disc , loading panel and controller. The sample is put in that hole and screwed with a pin. For rotation of the disc to take place,time period of revolution is set up initially in the control panel. The wear is shown in the monitor in micrometer.The frictional force is shown in KN. The machine is automatically stopped when the given time period is reached. The abrasive we used for studying wear is a steel surface without any emery paper or SiC paper on it.

Table 3.2 Specifications of the DUCOM wear and friction monitor.

Parameter	unit	Minimum	Maximum
Disc speed	RPM	10	800
Pin diameter	mm	2	10
Pin length	mm	10	50
Wear track dia	mm	10	80
Normal load N	N	0	100
Frictional force	N	0	100

3.3.1 Operating Parameters

The variables involved in wear test are:

- % Si in the Al-Si alloy
- Normal load
- Sliding velocity
- Sliding distance

3.3.2 Wear Measurement

Wear is directly measured from directly taking the data from the monitor. The monitor shows wear in micrometer and frictional force in KN. To study the effect of one parameter on the wear , all other parameters are fixed and the respective parameter is varied. Thus wear is studied.

CHAPTER 4

RESULTS AND DISCUSSION

RESULTS AND DISCUSSION

4.Results of wear tests

In the present investigation,Al 10% Si commercial alloy available in the market and Al-5% SiC composite fabricated by stir casting route are been used.The Physico-mechanical properties are been studied in this piece of work.

4.1 Hardness measurement

Hardness is the basic requirement of a material for use in specified machine parts. The Hardness of the sample are measured using vicker's Hardness tester at 300gf,each data point is the average of five readings.

Table 4.1 Showing Vicker's hardness value for as-cat alloys

Material	Hardness(HV)
Al-10% Si alloy	57.2
Al-SiC composite	90.7

4.2 Tribological studies

Al-Si alloys and Al-SiC composites are been used in automobile parts since years.Hence it is required to study the tribological behaviour and improvement for such materials. Aiming at these aspects sliding and erosion wear behaviour has been investigated.

4.2.1 Studies on sliding wear

The sliding wear tests are carried out for different time lengths and the wear charecteristics are been explained below:

4.2.1.1Effect of Strand Length on Sliding wear Of Al-10%Si sample

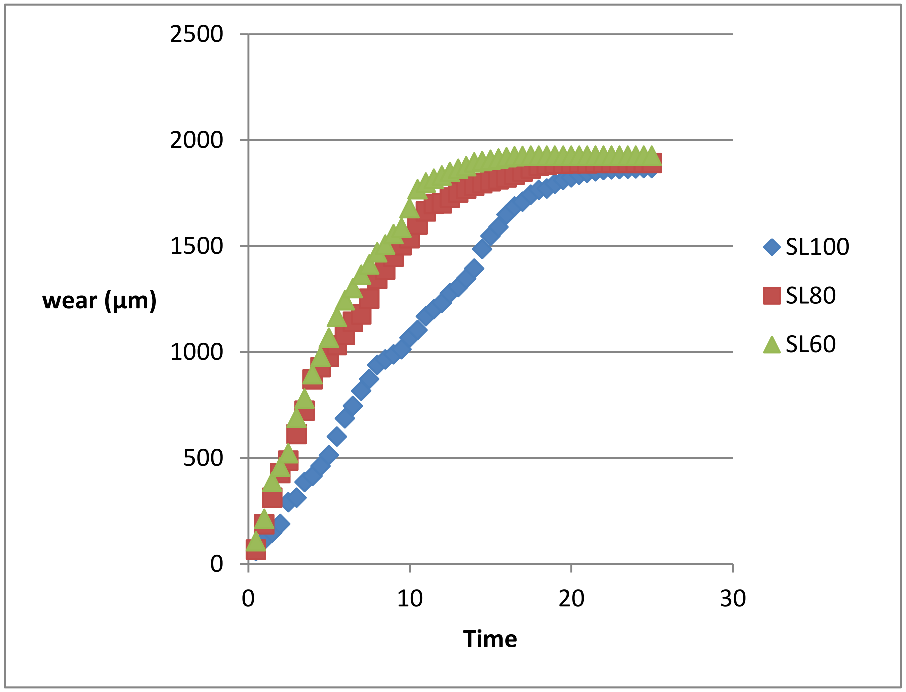

Fig 4.1 Effect of strand length on Dry sliding wear of Al-Si sample

The above figure shows that with increase in strand length , time required for the wear to be static also increases. This is because as the strand length increases, the track diameter decreases. So distance covered in one revolution also decreases. A static wear is achieved after the material has covered a certain distance. With smaller strand length, the sample will take more time to attain this distance. In this test for strand length 60 mm, static wear is achieved in a minimum time where for strand length 100 it is maximum. The test was done varying the strand length and keeping load (10KN) and sliding speed (100 RPM) as constant.

4.2.1.2 Effect of Sliding speed on wear of Al-Si sample

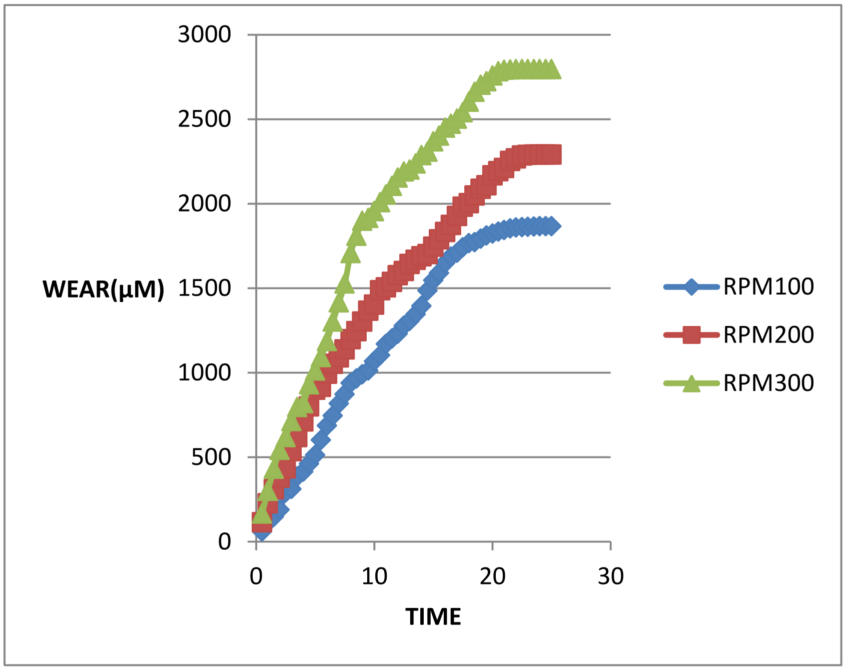

Fig 4.2 Effect of sliding speed on wear.

Wear is also dependent on sliding speed. Here the sliding speed is measured in RPM. The more is the sliding speed, the more distance will be covered by the sample. so static wear will be achieved faster .Wear will be higher for higher sliding speed. The above figure shows that with increase in sliding speed wear increases. From our figure it can be shown that at a particular time, wear is maximum for sliding speed 300 RPM where it is minimum for sliding speed 100 RPM.\

4.2.1.3Effect of Normal Load on wear of Al-Si sample

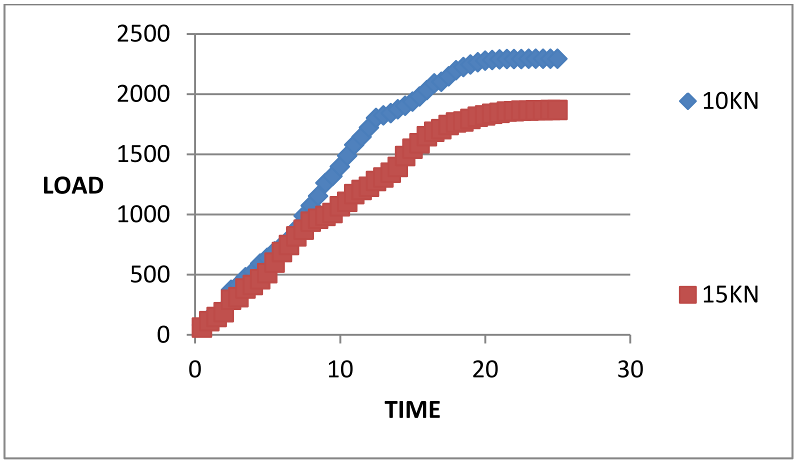

Fig 4.3 Effect of Normal load on wear

The more is the normal load, the more will be the wear. The tests were done varying the normal load and, keeping the strand length and sliding speed fixed. In atomic level the surface of a material can not be fully flat. When two surfaces are in contact, they touch each other at some points. when load is applied, plastic deformation occurs locally in those points which leads to removal of material. More the load more will be the plastic deformation. Hence wear will be more.

4.2.1.4Effect of Strand Length on Wear of Al-SiC Composite

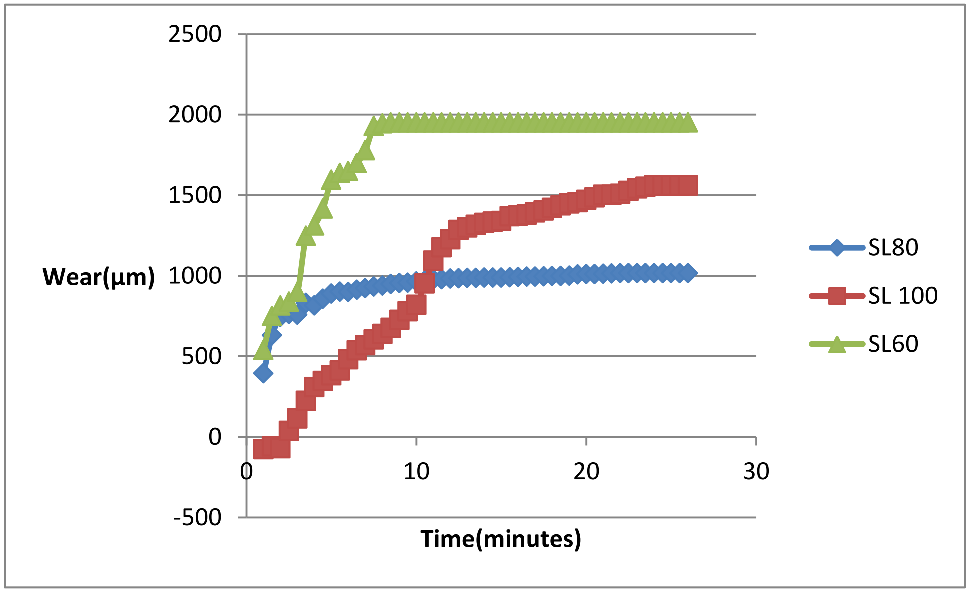

Fig 4.4 Effect of strand length on wear of Al-SiC composite

The effect of strand length on wear of Al-SiCp reinforced metal matrix composite is similar to its effect on wear of Al-Si alloy. The trend lines are similar in both case. Increase the strand length, smaller will be the track diameter. Hence to slide the same distance, sample tested under larger strand length condition will take more time before attaining the static wear than smaller strand length.

4.2.1.5 Effect of Normal load on wear of Al-SiC composite

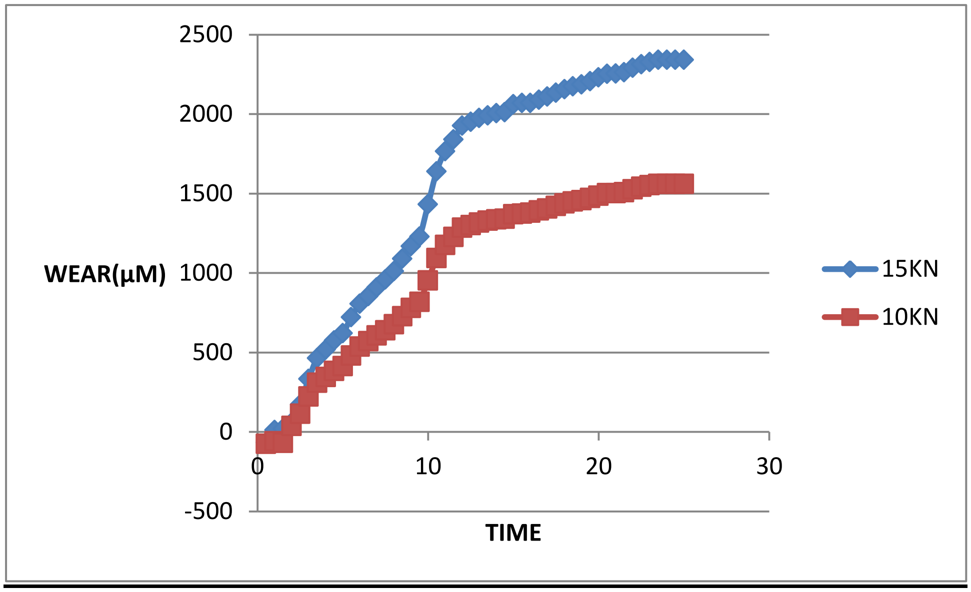

Fig.4.5 wear w.r.t time at different normal load

The above figure shows that at a particular time wear is higher for a higher load. No engineering surface is perfectly planar. some protuberance are present on the surface. There may be dirt or some other particle on the surface. When load is applied, those particles penetrate into the solid surface causing local plastic deformation. Material removes from those areas. Higher the load, higher will be the penetration and more will be the wear.

4.3 Studies on Erosion

The erosion wear tests are carried out at different impact angle and impact pressure.The results have been discussed below:

4.3.1 Solid Particle Erosion Wear Test Of Al-Si Alloy

4.3.1.1 Effect of Impact angle On Al-Si alloy

Solid particle erosion wear test was carried out

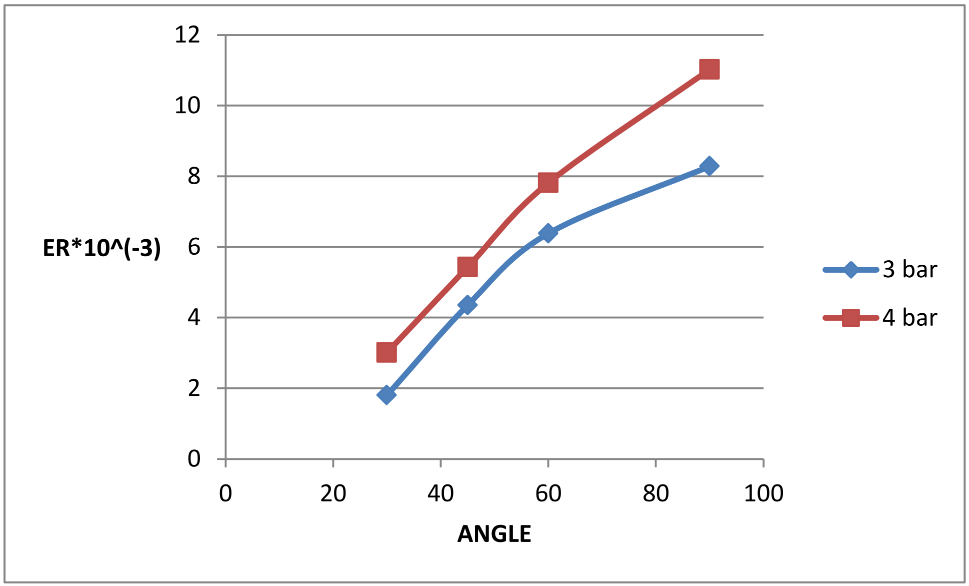

Fig4.6(a) Effect of angle on erosion wear rate after 60 secs.

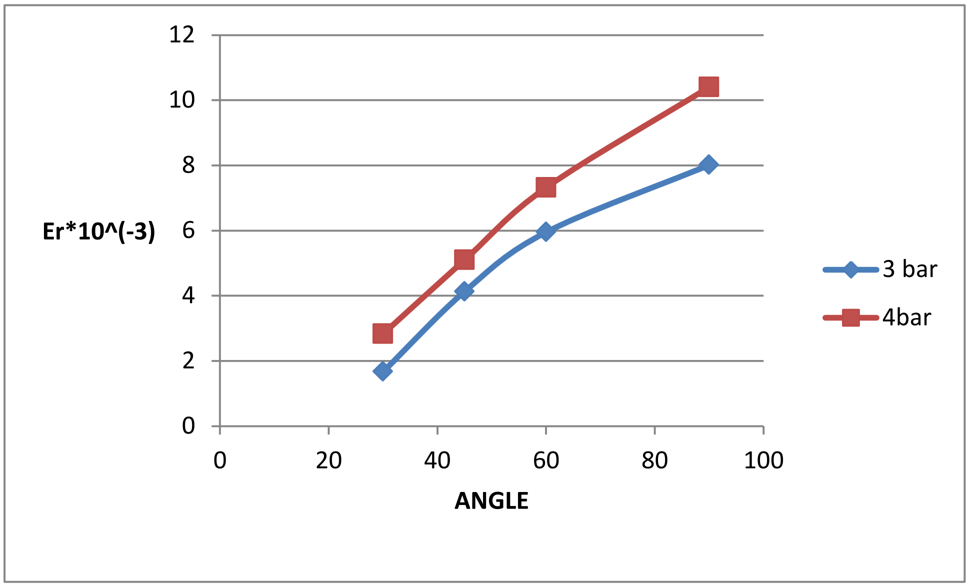

Fig4.6(b) Effect of angle on erosion wear rate after 120 secs.

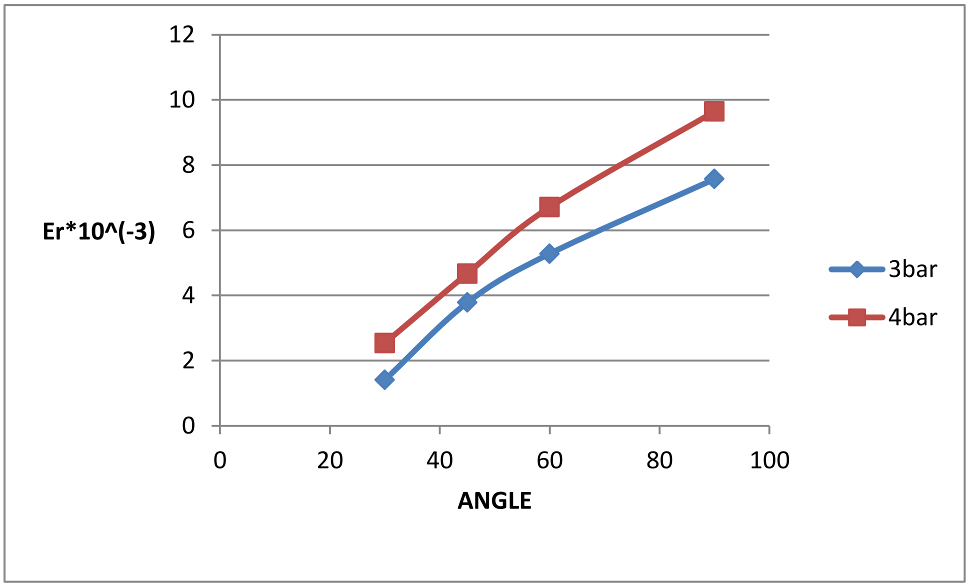

Fig 4.6(c) Effect of angle on erosion wear rate after 180 secs.

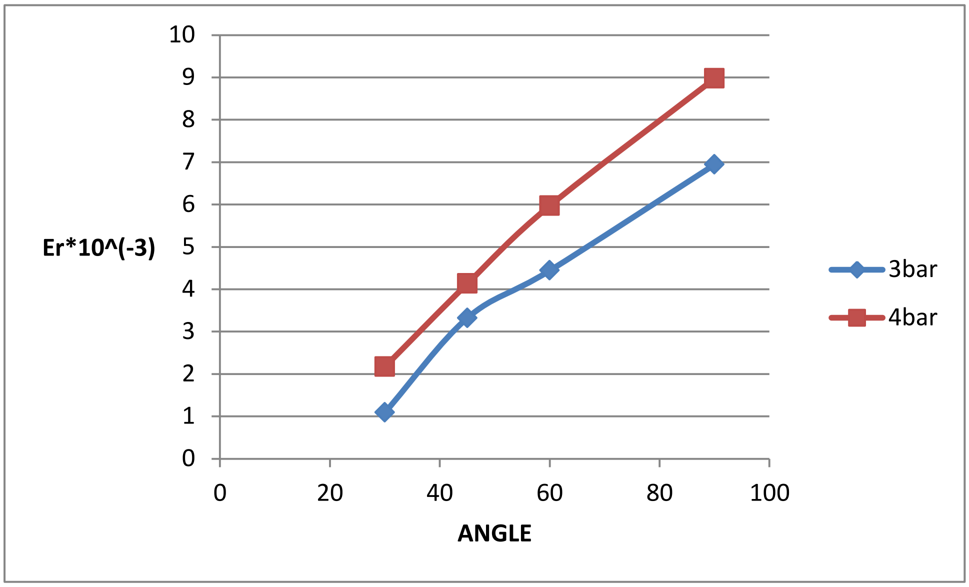

Fig4.6(d) Effect of angle on erosion wear rate after 240 secs.

The above figure shows that Erosion rate increases with increase in angle. When erodent particles strike the surface at an angle, it exerts two types of forces on the surface.One is the tangential force and other is the normal force. The tangential force tries to cause plastic deformation and the normal force

4.3.2 Effect of pressure on Al-Si alloy

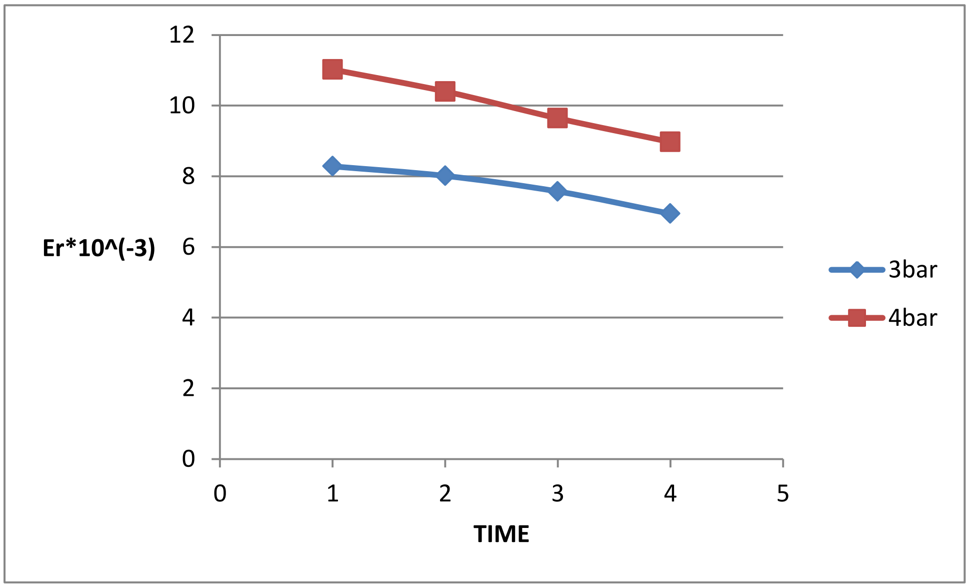

Fig 4.7Erosion rate against time at an impact angle 90°.

The figure shows that erosion wear rate decreases with increase in time.

4.3.3Effect of angle on Al-SiC composite

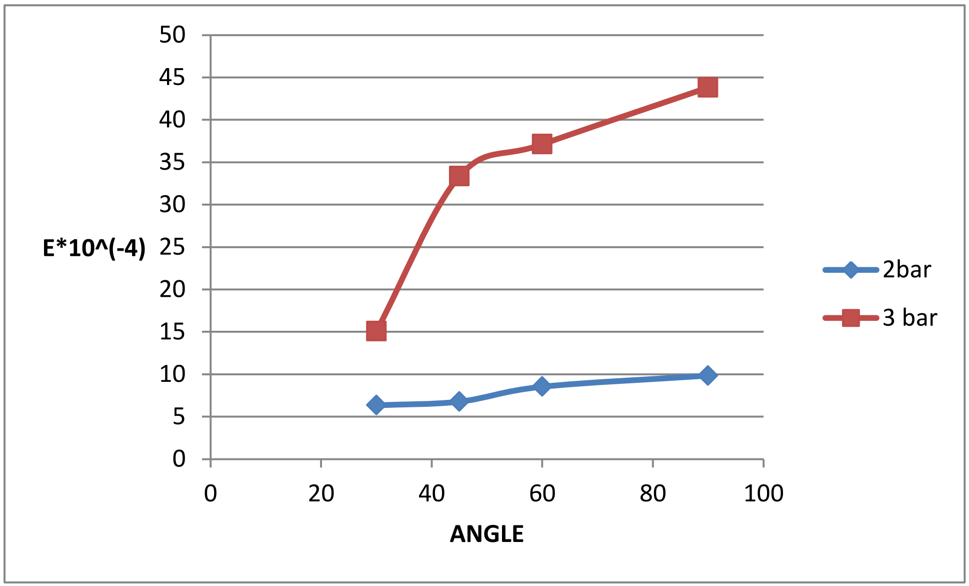

Fig 4.8(a) Effect of angle on ersoin wear rate In 60 secs.

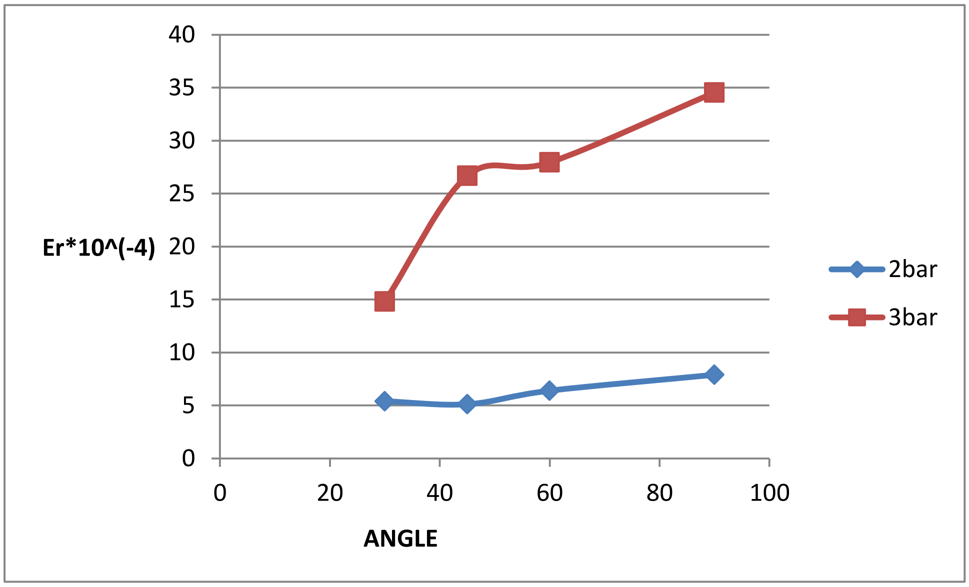

Fig 4.8(b) Effect of angle on ersoin wear rate In 120 secs.

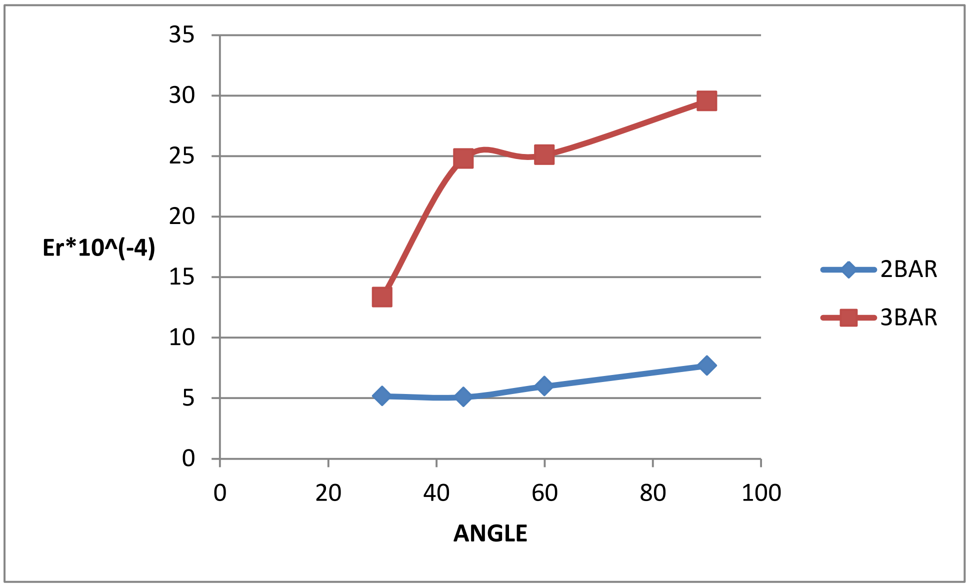

Fig 4.8(c) Effect of angle on ersoin wear rate In 180 secs.

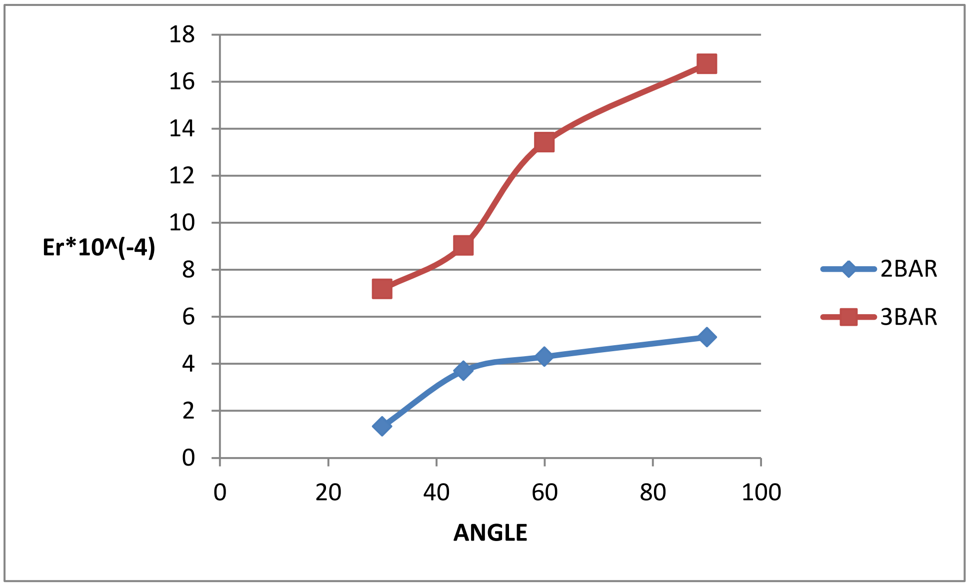

Fig 4.8(d) Effect of angle on ersoin wear rate In 240 secs.

From the above figures it can be concluded that wear increases with angle.

4.3.4 Effect of Pressure on Al-SiC composite

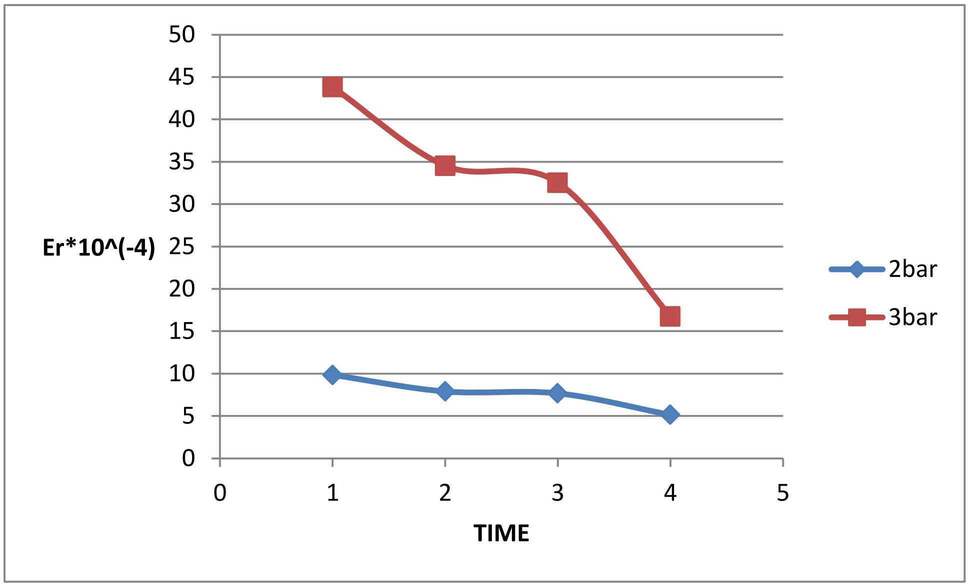

Fig 4.9 Erosion wear rate against time at an impact angle 90°.

4.4 Study of Sliding wear on Pin-on-Disc machine by WINDUCOM software

This software helps to visualize the wear and frictional force with respect to time on the computer screen. The figures given below explain how it work.

4.4.1 Study On Al-Sic composite

Wear was studied at load 5 KN and 10 KN, fixing the strand length 100 cm and Sliding speed 100 RPM. The time period is set for 10 minutes.

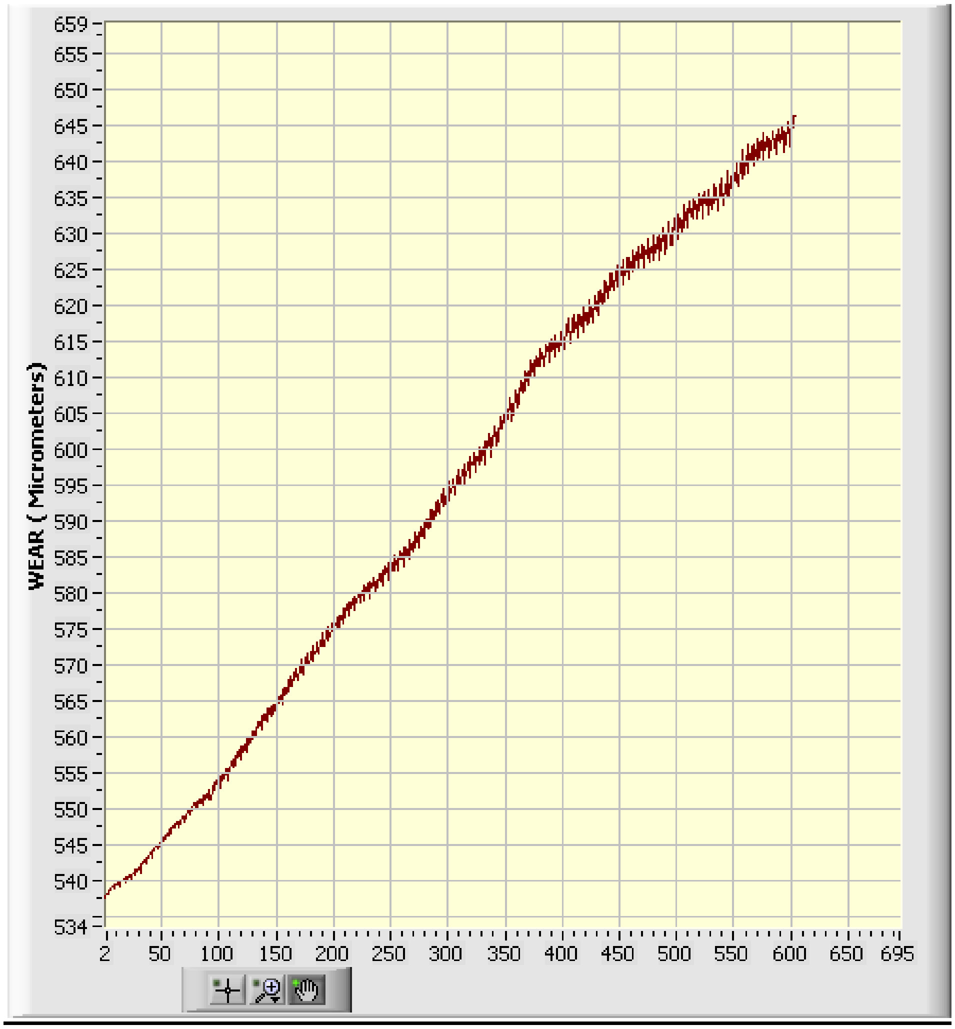

Fig 4.10 Wear at load 5 KN

This figure shows that within 10 minutes time, the static load is not reached. But the large fluctuations indicate that the material develops wear resistance gradually.

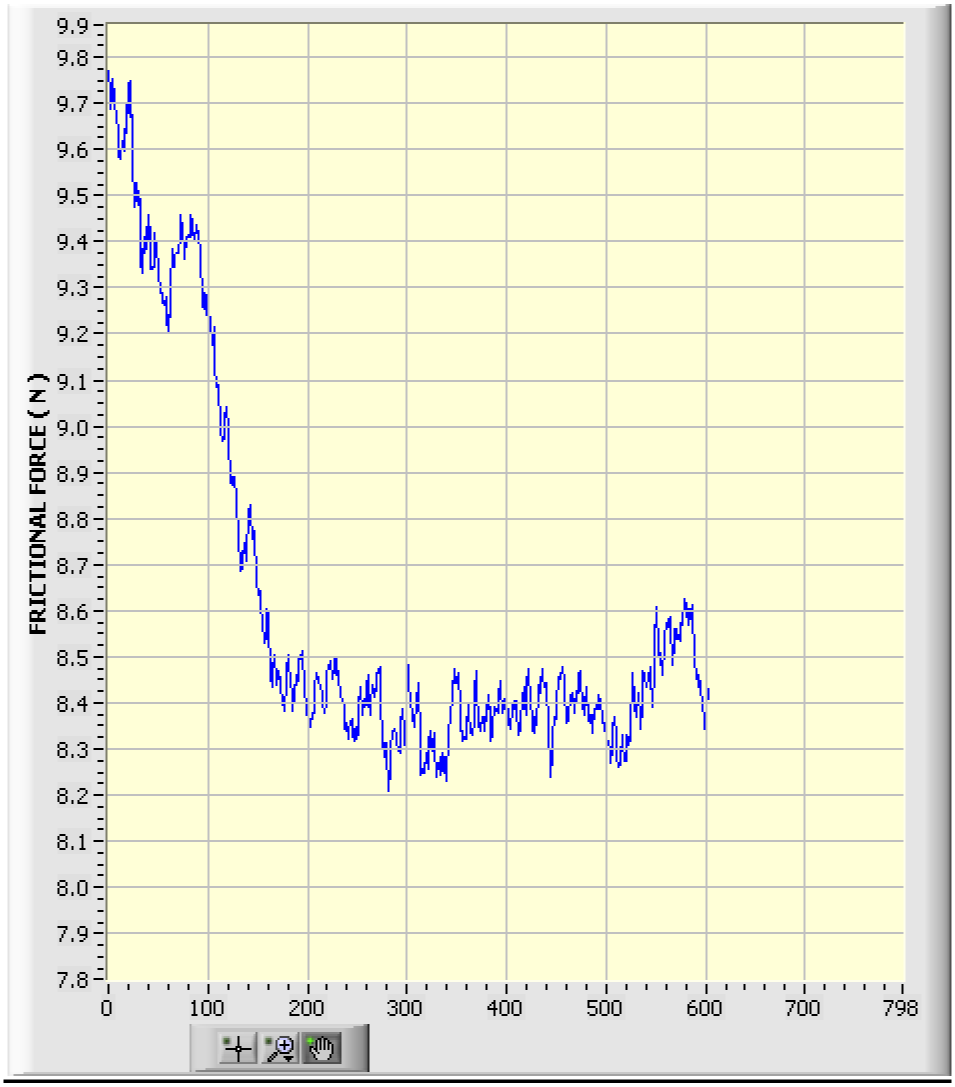

Fig 4.11 Frictional force variation with time

The figure shows that after some time the frictional force is attaining a constant value.

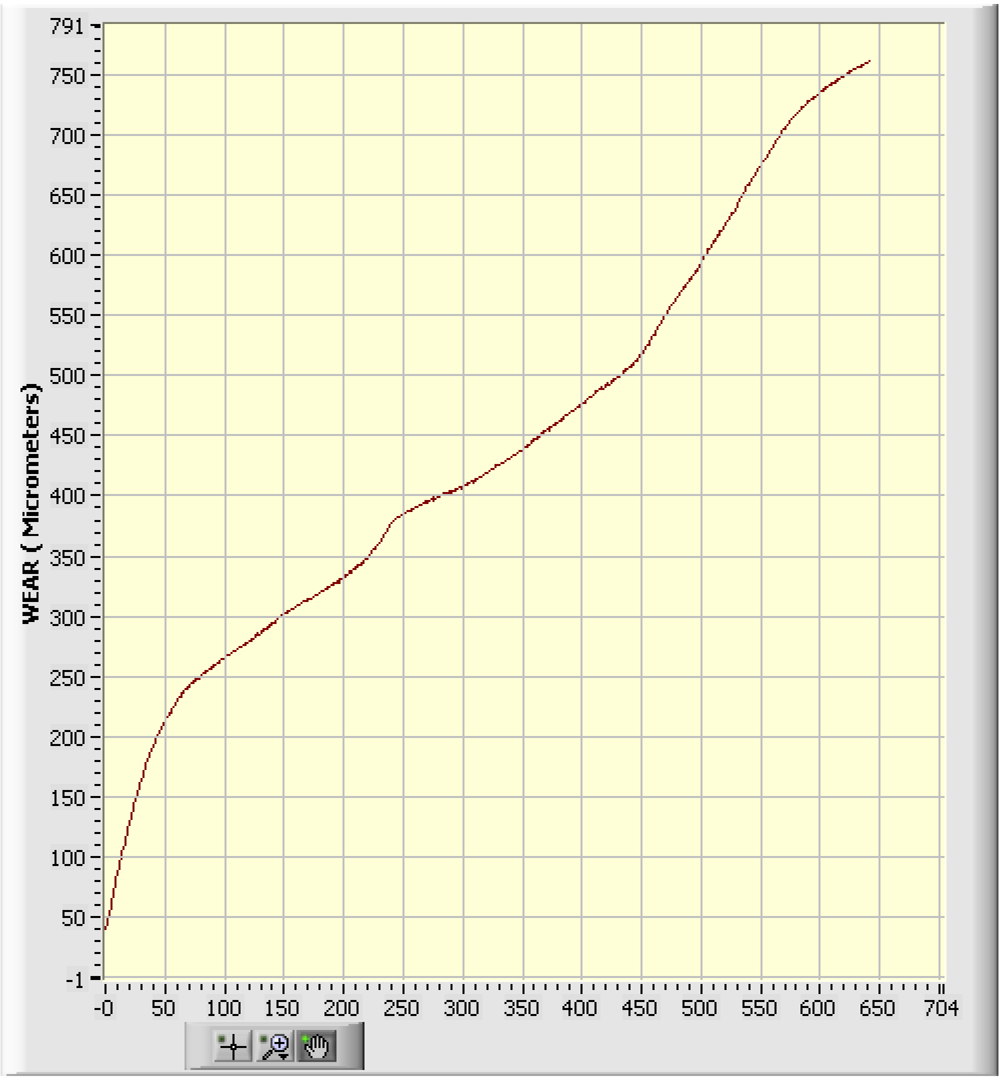

Fig 4.12 wear against time at 10 KN load

This figure shows that there are three different regions. Region 1(upto 50 secs),Region 2(upto 450 secs) and Region 3(upto 600 secs). Mechanism of wear may be different in the different regions. It has to be investigated.

Fig 4.13 Frictional force against time

4.5 Surface Morphology study

The surface morphology was investigated with a optical microscope at different resolutions

Figure 4.14: initial microstructure of AlSiC composite.

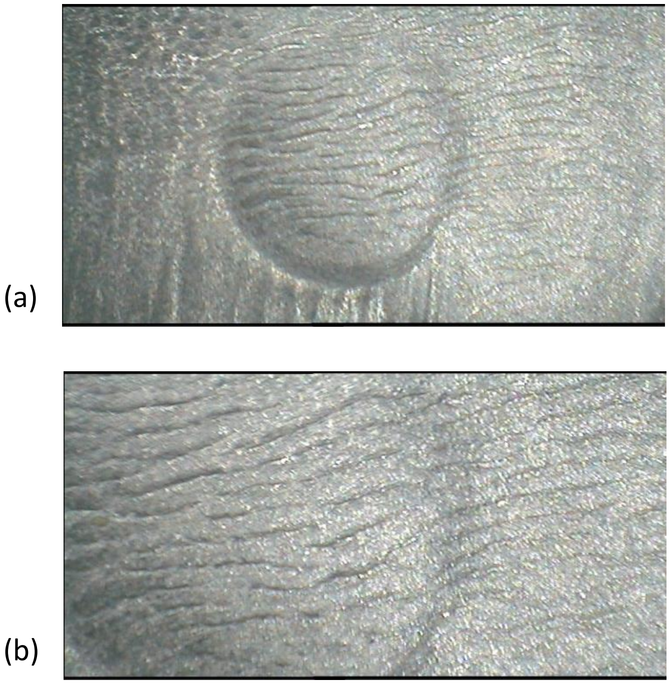

Figure 4.15: (a) Erosion wear at 60° angle, 3 bar pressure for 240Sec, (b) magnified to showing the wavy region.

CHAPTER 5

CONCLUSION

5.CONCLUSION

(1)Al-SiC particulate composite bears higher hardness than that of Al-10%Si alloy.

(2)The sliding wear behaviour of Al-SiCp material possess superior sliding wear sustanability than that of Al-10% Si alloy.

(3)The sliding wear rate is magnified more han two and half times than the Al-10%Si alloy,When SiC is used for making aluminium metal matrix composite.

(4)Erosion wear behaviour is also been affected with the hardness;which has been observed from the erosion wear tests.

(5)It is found that erosion angle and impact pressure are the main parameters for erosion of the material.

(6)It is observed that maximum erosion has taken place at 90° angle of impingement and the erosion amount is less with Al-SiCp than that of Al-10%Si alloy.

(7)Hence it can be concluded that the hardness of the material,sliding distance and applied pressure are responsible for sliding wear behaviour; the hardness of the erodant and angle of impingement are the major factors for erosion wear.

CHAPTER 6

REFERENCES

References

[1] V. Turkel, C. Tekmen, SiC–AlSi Composite Coatings on Piston Alloys for Diesel Engine Motors, Journal of Composite Materials, DOI: 10.1177/0021998304042744.

[2]Soykan, S., Ustel, F., Celik, E. and Avci, E. (1997). Investigation of Friction and Wear Behaviours of Plasma Sprayed Ceramic Coating, Journal of Turkish Eng. and Environ. Sciences, 21: 417-423.

[3] Celik, E., Avci, E. and Yilmaz, F. (1997). Evaluation of Interface Reactions in Thermal Barrier Ceramic Coatings, Surface and Coatings Tech., 97: 361-365.

[4] Demirkiran, A.S., Celik, E., Yargan, M. and Avci, E. (2001). Oxidation Behaviour of Functionally Gradient Coatings Including Different Composition of Cermets, Surface and Coatings Tech., 142–144: 551–556.

[5] Keribar, R. and Morel, T. (1987). Methods for Thermomechanical Analysis of Thermal Barrier Coatings in Diesel Engines, Surface and Coatings Tech., 30: 63-71.

[6]. DeMasi-Marcin, J.T. and Gupta, D.K. (1994). Protective Coatings in the Gas Turbine Engine, Surface and Coatings Tech., 68–69: 1–9.

[7] Celik, E. and Avci, E. (1999). Effect of Grit Blasting of Substrate on the Corrosion Behaviour of Plasma-Sprayed Al2O3 Coatings, Surface and Coatings Tech., 116-119: 1061-1064.

[8] Shrestha, N.K., Sakurada, K., Masuko, M. and Saji, T. (2001). Composite Coatings of Nickel and Ceramic Particles Prepared in Two Steps, Surface and Coatings Tech., 140: 175–181.

[9] M.M. Haque A. Sharif /Study on wear properties of aluminium–silicon piston alloy/Journal of Materials Processing Technology/Volume 118, Issues 1–3, 3 December 2001

[10] A.T. Alpas, J. Zhang/Effect of SiC particulate reinforcement on the dry sliding wear of aluminium-silicon alloys/Wear/Volume 155, Issue 1, 15 May 1992.

[11] Dheerendra Kumar Dwivedi/Wear behaviour of cast hypereutectic aluminium silicon alloys/Materials & Design Volume 27, Issue 7, 2006,

[12] N. Axén,I.M. Hutchings.S. Jacobson/A model for the friction of multiphase materials in abrasion/Tribology International

[13]y.sahin/ Wear Behavior of Al-Al2O3 Reinforced Composites/ Advanced Materials Research (Volumes 308 - 310)/ Advanced Design Technology

[14] Tuti Y. Alias and M.M. Haque/ WEAR PROPERTIES OF ALUMINUM – SILICON EUTECTIC ALLOY.

[15] E. Candan a, H. Ahlatci b, H. Ç¨ımenoˇglu b;/ Abrasive wear behaviour of Al–SiC composites produced by pressure infiltration technique/ Wear 247 (2001) 133–138

[16] Vencl Aleksandar, "Scientific problems of machines operation and maintenance" 3 (159) 2009, Tribology Laboratory, Mechanical Engineering Faculty, University of Belgrade

[17] Kori S A, Chandrashekharaia T M, "Studies on the dry sliding wear behaviour of hypoeutectic and eutectic Al–Si alloys", Wear,Volume 263 (2007), pages-745-755.

[18] Rajaram G, Rao T. Srinivas, "High temperature tensile and wear behaviour of aluminum silicon alloy", Materials Science and Engineering A 528 (2010),pages - 247-253.

[19] Torabian H, Pathak JP and Tiwari SN, "Wear characteristics of Al-Si alloys", Wear, volume172 (1994) , pages 49-58

[20] Singla Manoj, Singh Lakhvir, Chawla Vikas, "Journal of Minerals and Materials Characterization and Engineering, Vol. 8, No.10, pages 813-819, 2009.

[21] P.L. Ko, "Metallic Wear-A Review with Special References to Vibration-Induced Wear in Power Plant Components", Tribology International, Vol. 20, No. 1, 66-78, 1987.

[22] L.S. Eyre, "Wear Characteristics of Metals", Tribology International, 203-212, 1976.

[23] J. Blau, "Fifty Years of Research on the Wear of Metals." Tribology International, Vol. 30, No. 5, 321-331, 1997.