SYNTHESIS OF Al-Si ALLOYS AND STUDY OF THEIR MECHANICAL PROPERTIES

A THESIS IN PARTIAL FULFILMENTS OF REQUIREMENTS
FOR THE AWARD OF THE DEGREE OF

Bachelor of Technology

Submitted to

NATIONAL INSTITUTE OF TECHNOLOGY, ROURKELA

BY

Soumyajit Nayak
107MM004

Anand Karthik K V N B
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DEPARTMENT OF METALLURGICAL & MATERIALS ENGINEERING

NATIONAL INSTITUTE OF TECHNOLOGY

ROURKELA – 769008

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DEPARTMENT OF METALLURGICAL & MATERIALS ENGINEERING

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<u>CERTIFICATE</u>

This is to certify that the Thesis entitled "Synthesis of Al-Si Alloys and Study of their Mechanical Properties" submitted by Soumyajit Nayak (Roll No.107MM004) & Anand Karthik KVNB (Roll No.107MM036), Department of Metallurgical and Materials Engineering, National Institute of Technology, Rourkela, as a partial fulfilment of requirements for the award of the Degree of Bachelor Of Technology has been carried out under my supervision and has not been submitted elsewhere fancy award of any degree.

Prof. K. Dutta

Department of Metallurgical

And Materials Engineering

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Date:

Soumyajit Nayak (107MM004)

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ABSTRACT

Within the last few years there has been a rapid increase in the utilisation of aluminium-silicon alloys, particularly in the automobile industries, due to their high strength to weight ratio, high wear resistance, low density and low coefficient of thermal expansion. The advancements in the field of application make the study of their wear and tensile behaviour of utmost importance. In this present investigation, Aluminium based alloys containing 7%, 12% and 14% weight of Silicon were synthesized using casting method. Compositional analysis and tensile studies of different samples of same composition have shown near uniform distribution of Si in the prepared alloys. Study of microstructure has showed the presence of primary silicon. Tensile tests were carried out with universal testing machine. Yield strength and ultimate tensile strength has increased with increase in silicon percentage. Wear behaviour was studied by using computerized pin on disc wear testing machine. Resistance to wear has increased with increase in silicon amount. The worn surfaces were analysed using scanning electron microscope.

Keywords: Al-Si alloys, casting, wear, microstructure

CHAPTER – 1

INTRODUCTION

1.1 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 materials[1].

1.2 Aluminium alloys

In recent years aluminium alloys are widely used in automotive industries. This is particularly due to the real need to weight saving for more reduction of fuel consumption. The typical alloying elements are copper, magnesium, manganese, silicon, and zinc. Surfaces of aluminium alloys have a brilliant lustre in dry environment due to the formation of a shielding layer of aluminium oxide. Aluminium alloys of the 4xxx, 5xxx and 6xxx series, containing major elemental additives of Mg and Si, are now being used to replace steel panels if various automobile industries. Due to such reasons, these alloys were subject of several scientific studies in the past few years[2].

1.3 Designation of Aluminium alloys

On the basis of the major alloying element, the aluminium alloys are designated according to the Aluminium Association Wrought Alloy Designation System which consists of four numerical digits[3].

Table 1.1 Designation of aluminium alloys and their applications

Alloy	Main alloying element	Applications
1xxx	Mostly pure aluminum; no major alloying additions	Electrical and chemical industries
2xxx	Copper	Aircraft components
3xxx	Manganese	Architectural applications
4xxx	Silicon	Welding rods, automobile parts
5xxx	Magnesium	Boat hulls, marine industries
6xxx	Magnesium and silicon	Architectural extrusions
7xxx	Zinc	Aircraft components
8xxx	Other elements (e.g., Fe, Ni or Ti)	
9xxx	Unassigned	

1.4 Properties of Aluminium alloys

A wide range of physical and mechanical properties can be obtained from very pure aluminium. The different properties are:

1) Aluminium has a density of about 2.7g/cc which is one third (approximately) the value of steel.
2) Unlike steel, aluminium prevents progressive oxidation by formation of a protective oxide layer on its surface on exposure to air.
3) Aluminium alloys exhibit excellent electrical and thermal conductivities. The thermal conductivity of aluminium is twice that of copper (for the same weight of both materials used).

1.5 Aluminium-Silicon alloy

Aluminium-Silicon alloys are of greater importance to engineering industries as they exhibit high strength to weight ratio, high wear resistance, low density, low coefficient of thermal expansion etc. Silicon imparts high fluidity and low shrinkage, which result in good castability and weldability. Al-Si alloys are designated 4xxx alloys according to the Aluminium Association Wrought Alloy Designation System. The major features of the 4xxx series are:

a. Heat treatable
b. Good flow characteristics, medium strength
c. Easily joined, especially by brazing and soldering

There are two major uses of the 4xxx series – for forging and weld filler alloy. These both applications are due to the excellent flow characteristics provided by relatively high silicon content.

Effects of silicon in the Al-Si alloys are as follows[4]:

i. Thermal expansion is reduced substantially by silicon
ii. Magnetic susceptibility is only slightly decreased by silicon
iii. The lattice parameter is decreased slightly by silicon
iv. Machinability is poor because of the hardness of the silicon

Although many investigations exist in literature and based on the above discussion, it is evident that there is enough scope for further research of Al-Si alloys especially their mechanical properties. Therefore the objectives of this study are;

i) Preparation of Al-Si alloys of hypo and hyper eutectic compositions.
ii) To study of their microstructure.
iii) To study of their mechanical properties.
iv) To evaluate their wear behaviour.

CHAPTER – 2

LITERATURE REVIEW

2.1 Introduction

Aluminium alloy are gaining huge industrial significance because of their outstanding combination of mechanical, physical and tribological properties over the base alloys. These properties include high specific strength, high wear and seizure resistance, high stiffness, better high temperature strength, controlled thermal expansion coefficient and improved damping capacity. It is reported that Aluminium alloy reinforced with around 10 wt% SiC particle composite offers similar mechanical properties but enhanced thermal conductivity and specific heat than the cast irons. Consequently, frictional heating of these alloys are found to be significantly less than that of cast irons. This leads to their excessive use in many automobile and engineering sectors where wear, tear and seizure are the major problems in addition to the weight saving. Some of these components are cylinder heads, pistons, connecting rods and drive shafts for automobile industries and impellers, agitators, turbine blade, valves, pump inlet, vortex finder in many marine and mining sectors[5].

2.2 Al-Si Alloy

2.2.1 Introduction

Aluminium alloys are distinguished according to their major alloying elements. The 4xxx group contains silicon as the main alloying element for ease of casting. Silicon is good in metallic alloys. This is because it increases the fluidity of the melt, reduces the melting temperature, decreases the shrinkage during solidification and is very inexpensive as a raw material.

Silicon also has a low density (2.34 g cm^{-3}), which may be an advantage in reducing the total weight of the cast component. Silicon has a very low solubility in aluminium; it therefore precipitates as virtually pure silicon, which is hard and hence improves the abrasion resistance. Aluminium-silicon alloys form a eutectic at 12.6 wt% silicon, the eutectic temperature being 577°C. This denotes a typical composition for a casting alloy because it has the lowest possible melting temperature[6].

2.2.2 Phase Diagram

Aluminium-Silicon system is a simple binary eutectic with limited solubility of aluminium in silicon and limited solubility of silicon in aluminium. There is only one invariant reaction in this diagram, namely

$L \rightarrow \alpha + \beta$ (eutectic)

In above equation, L is the liquid phase, α is predominantly aluminium, and β is predominantly silicon. It is now widely accepted that the eutectic reaction takes place at 577°C and at a silicon level of 12.6%.

Aluminium-Silicon (Al-Si) casting alloys are the most useful of all common foundry cast alloys in the fabrication of pistons for automotive engines. Depending on the Si concentration in weight percentage, the Al-Si alloy systems are divided into three major categories:

i. Hypoeutectic (<12 wt % Si)
ii. Eutectic (12-13 wt % Si)
iii. Hypereutectic (14-25 wt % Si).

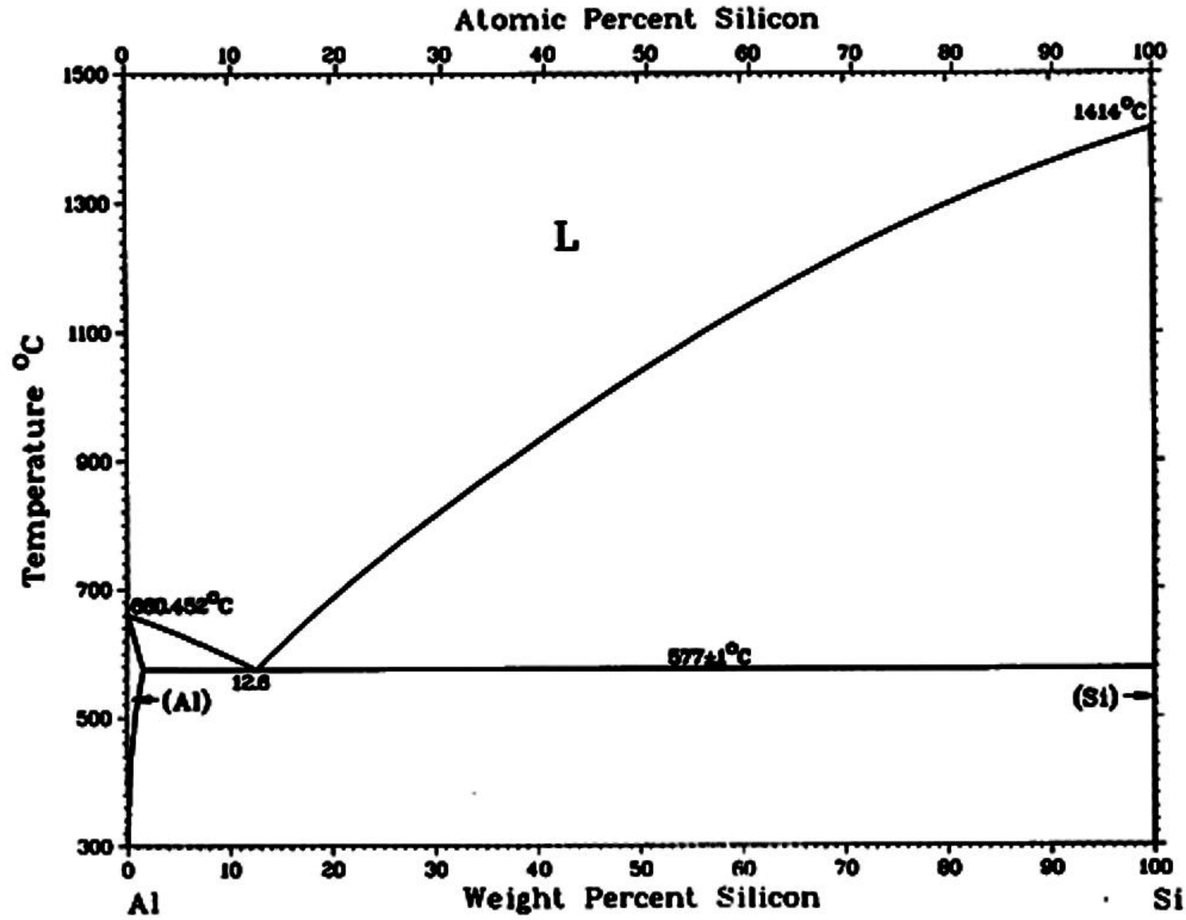

Fig. 2.1 Al-Si phase diagram[7]

2.2.3 Uses of Al-Si alloys

Recent examples of aluminium applications in vehicles cover, power trains, chassis, body structure and air conditioning. Aluminium castings have been applied to various automobile parts for a long period. As a key trend, the material for engine blocks, which is one of the heavier parts, is being switched from cast iron to aluminium resulting in significant weight reduction. Aluminium castings find the most widespread use in automobile. In automotive power train, aluminium castings have been used for almost 100% of pistons, about 75% of cylinder heads, 85% of intake manifolds and transmission (other parts-rear axle, differential housings and drive shafts etc.) For chassis applications, aluminium castings are used for about 40% of wheels, and for brackets, brake components, suspension (control arms, supports), steering components (air bag supports, steering shafts, knuckles, housings, wheels) and instrument panels.

Forged wheels have been used where the loading conditions are more extreme and where higher mechanical properties are required. Aluminium alloys have also found extensive application in heat exchangers. Modern, high performance automobiles have many individual heat exchangers, e.g. engine and transmission cooling, charge air coolers (CACs), climate control, made up of aluminium alloys[8].

Al-Si is an important alloy for many commercial automotive applications (pistons, cylinder liners, etc.) duo to its unique properties. Al-Si casting alloy are the most versatile of all common foundry cast alloys in the production of pistons for automotive engines.

Commercial uses for hypereutectic alloys are comparatively limited because these are the most difficult Al alloys to cast and machine due to the high Si contents. Once high Si content is alloyed into Al, it adds a large amount of heat capacity that must be removed from the alloy to solidify it during the casting operation. Major variation in the sizes of the primary Si particles can be found between different areas of the cast structure, causing significant deviation in the mechanical properties for the specimen. The primary crystals of Si must be refined so as to accomplish better hardness and wear resistance. Due to these reasons, hypereutectic alloys are not very cost-effective to fabricate because they have a broad range of solidification that results in poor castability and requires extra foundry processes to control the microstructure and the high heat of fusion.

On the other hand, the usage of hypoeutectic and eutectic alloys is very widespread in the industries, because they are:

a. more efficient to produce by casting
b. simpler to control the cast parameters
c. easier to machine than hypereutectic.

But, most of them are not appropriate for high temperature applications, such as in the automotive field, for the reason that their mechanical properties, such as tensile strength, are not as high as anticipated in the temperature range of 250°C - 400°C [9].

2.2.4 Microstructure

Binary Al-Si alloys, in the unmodified state, near to the eutectic composition exhibit acicular or lamellar eutectic silicon which is in the form of large plates with sharp sides and edges. Al-Si alloys containing more than about 12% Si exhibit a hypereutectic microstructure normally containing primary silicon phase in a eutectic matrix. Cast eutectic alloys with coarse acicular silicon show low strength and ductility because of the coarse plate-like nature of the Si phase that leads to premature crack initiation and fracture in tension. Similarly, the primary silicon in normal hypereutectic alloys is usually very coarse and imparts poor properties to these alloys. Therefore, alloys with a predominantly eutectic structure must be modified to ensure adequate mechanical strength and ductility. It is widely recognized that the Group IA and IIA elements (Na, Mg, Ca, Sr) are effective modifiers of Al-Si eutectic; only sodium and strontium, however, have been used extensively in the commercial production of these alloys. Refinement of primary silicon is usually achieved by the addition of phosphor to the melt. It is also reported that rare earth metals are also capable of modifying the eutectic structure of cast aluminium-silicon alloys[10]. Fig. 2.2 to Fig. 2.7 show microstructures of different Al-Si alloys.

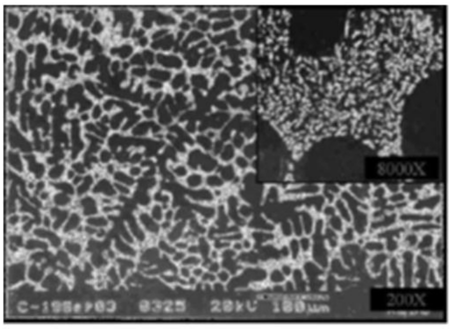

Fig 2.2 Microstructure of Al-7% Si[11]

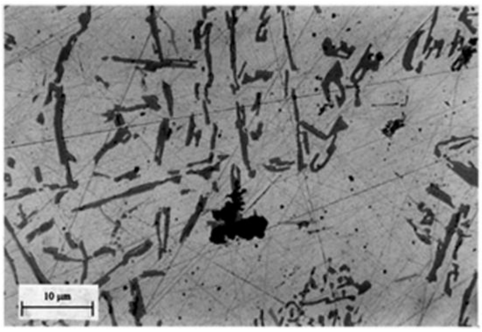

Fig 2.3 Microstructure of Al-12% Si[6]

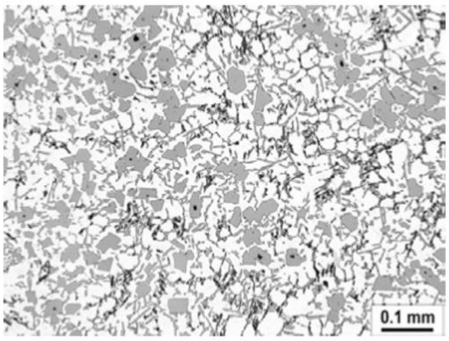

Fig 2.4 Microstructure of Al-16% Si[12]

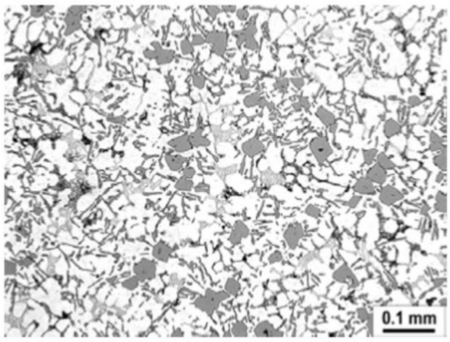

Fig 2.5 Microstructure of Al-18% Si[12]

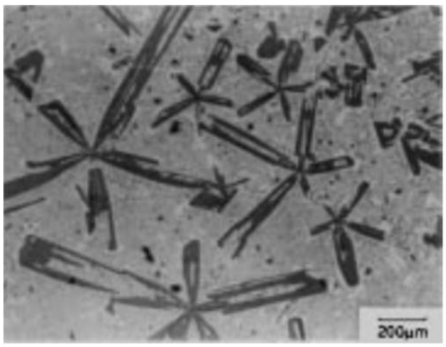

Fig 2.6 Microstructure of Al-21% Si[10]

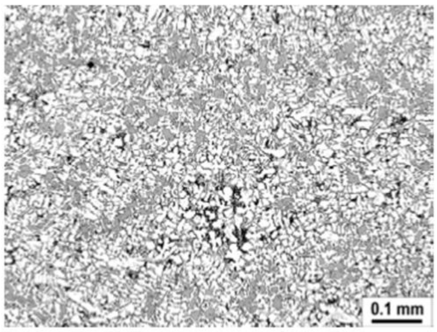

Fig 2.7 Microstructure of Al-22% Si[12]

2.2.5 Effect of Grain Refiner

Hypo-eutectic aluminium-silicon alloys have a huge portion of primary α-Al in their microstructure. An unmodified Al–Si alloy has large, brittle flakes of silicon, which result in poor ductility to the casting. Modifiers are added to eutectic and hypo-eutectic Al–Si alloys to refine the eutectic Si phase from angular platelets to fine fibres. This change in microstructure results in an additional development in the mechanical properties. The quality of the castings can be enhanced by grain refinement which decreases the size of primary α-Al grains in the castings, which else solidifies with a coarse, columnar grain structure. A fine equiaxed structure has many advantages like improved mechanical properties, better feeding during solidification, reduced and more evenly distributed shrinkage porosity, better dispersion of second phase particles, better surface finish and other desired properties. Al-Ti master alloys such as Al-3Ti-3B and Al-5Ti-1B alloys can be used for grain refinement of aluminium-silicon alloys[11].

2.2.6 Mechanical Properties

Wislei R. Osório et.al[13]. studied the effect of microstructure on mechanical properties for Al – 9wt% Si. Mechanical properties of Al–Si casting alloys depend not only on their chemical composition but are also significantly dependent on microstructural features such as the morphologies of the Al-rich α-phase and of the eutectic Si particles. Table 2.1 presents the experimental results of ultimate tensile strength (UTS), yield strength (YS), elongation (δ) and Vickers hardness (HV) for Al-9wt% Si alloy sample.

Table 2.1 Ultimate and yield tensile strengths (UTS and YS), elongation (d), Vickers hardness (HV) of Al-9wt% Si sample[13].

UTS (MPa)	**YS (MPa)**	**δ (%)**	**HV**
142	65	8	72

The effects of silicon on the mechanical properties of Al-Si alloys are well studied. The mechanical properties of the Al-Si alloy are dependent on the size, shape and distribution of eutectic and primary silicon particles. Small, spherical, uniformly distributed silicon particles enhance the strength properties of Al-Si alloys. The effect of composition on mechanical properties of Al-Si alloys is shown in following table 2.2.

Table 2.2 Mechanical Properties of Al-Si alloys[14]

Composition (wt%)	Ultimate tensile strength (MN m^{-2})	0.2% tensile proof stress (MN m^{-2})	Elongation (%)	Hardness (VHN)	Density (kg m^{-3}x 10^3)
Al-2%Si	127.3	52.6	12.4	39.5	2.68
Al-4%Si	142.2	58.3	10.2	47.3	2.67
Al-6%Si	155.7	64.8	9.6	55.6	2.65
Al-8%Si	169.6	71.5	7.2	61.6	2.62
Al-11.6%Si	185.4	80.0	5.8	67.0	2.59
Al-12.5%Si	189.0	82.5	5.4	70.0	2.57
Al-15%Si	183.25	77.7	4.7	72.5	2.55
Al-17%Si	175.8	73.7	3.0	76.6	2.53
Al-20%Si	172.4	72.0	2.5	81.0	2.50

It may be observed that as the amount of silicon in the alloy increases, the strength properties of Al-Si alloys also increase up to the eutectic composition, after which they show a decline with further increase in the silicon content. However, the hardness increases and the elongation (%) decreases continuously with increasing silicon content. This may be largely attributed to the size, shape and distribution of silicon particles in the cast structures up to the eutectic composition. Silicon is present as fine particles and is uniformly distributed in the structure, and hence the strength properties increase. However, when the primary silicon appears as coarse polyhedral particles, the strength properties decrease with increasing silicon content, but the hardness goes on increasing because of the increase in the number of silicon particles[14].

2.2.6 Wear Behaviour

Study of wear behaviour has very much importance in several automobile and engineering industries because wear, tear and seizure of components are major problems in such industries. Sliding wear behaviour and abrasive wear behaviour of Al-alloy has been studied by many investigators. According to these reports, wear and seizure resistance of Al-alloy is significantly higher than that of the base alloys. This is mainly credited to the fact that the hard dispersoids (reinforcing phase) protect the surface from the destructive act of the abrasives by decreasing the depth of penetration of the abrasives and the contact between the abrasive and the matrix. On the other hand, few investigators have reported a changeover of abrasive wear behaviour of alloys which was reliant on abrasive size and applied load. Also, it is apparent from the literature that the wearing surface and the subsurface experience plastic deformation, and this deformation become more severe when the abrasive size is coarser and the applied load is higher. The abrasive wear behaviour of alloy depends on the material characteristics like size, distribution, shape and volume fraction of the dispersoids and experimental parameters like applied load and abrasive size. It has been observed that the wear resistance of alloy increases with rise in volume fraction and size of the dispersoids. One of the important factors of the improvement in wear resistance is increase in hardness of the Al-alloy due to the addition of hard dispersoids and better protection of the matrix from the destructive action of the abrasive as the mean free path between the SiC particles is reduced with increase in volume fraction of SiC particle. Several investigators have proposed that wear resistance of a material also depends on its ductility and toughness. The reinforcement of Al_2O_3 particles in aluminium alloy enhances the abrasive wear of the matrix. The reinforcement of coarse particle shows better wear resistance[5].

Chen et al.[15] investigated wear mechanisms in eutectic Al–Si alloys (11–12% Si) tested against a hard steel counterface and observed that the advancement of damage events generally comprised of the following steps:

(i) Wear of the top surfaces of silicon particles by the counterface.

(ii) Embedding of silicon particles into aluminium matrix (or particle sinking-in).

(iii) Plastic deformation of aluminium causing the formation of aluminium pile-ups adjacent to the sunken-in silicon particles.

(iv) Wear of the elevated portions of aluminium plateaus by the counterface.

The following graphs obtained from the tests by Das et al.[5] show the variation of the wear rate of Al alloy as a function of sliding distance under different applied loads.

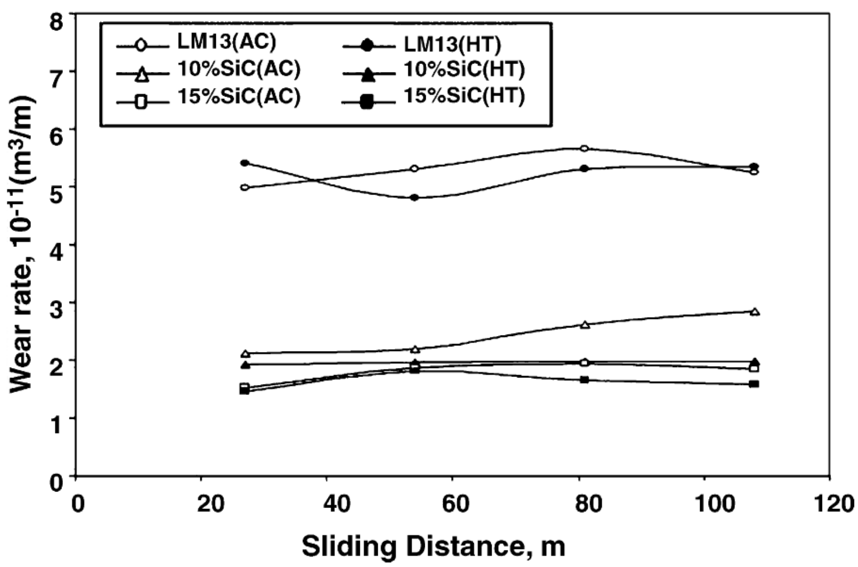

Fig. 2.8 Wear rate of Al alloy as a function of sliding distance (applied load: 1N)

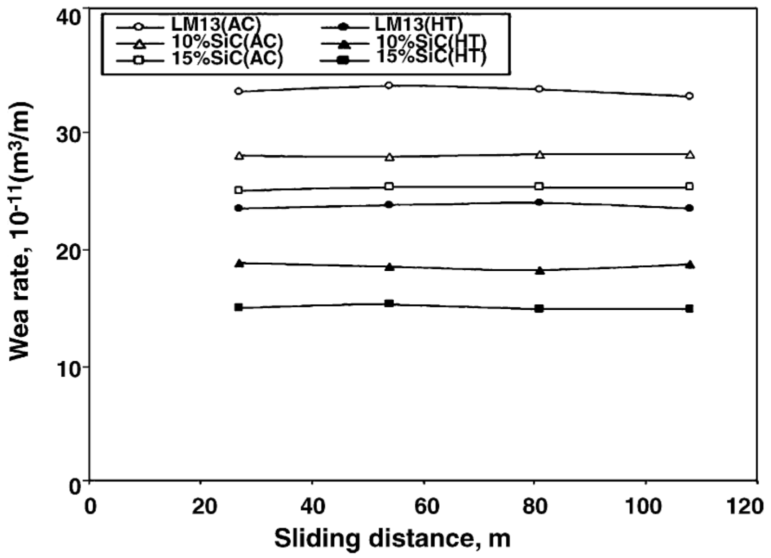

Fig. 2.9 Wear rate of Al alloy as a function of sliding distance (applied load: 7N)

CHAPTER – 3

EXPERIMENTAL

3.1 Introduction

Aluminium-silicon alloys were prepared with different weight percentage of silicon by stir casting route in an induction heating furnace. Samples of different dimensions were cut for different tests. Their composition was analysed with the help of an optical emission spectrometer. Wear behaviour of different composition samples were studied by conducting several wear tests on computerized Ducom friction and wear monitor pin on-disc wear test machine. The microstructures of the samples and of the worn surfaces were observed under a scanning electron microscope. The hardness was measured with the Vickers hardness testing machine. The tensile properties were obtained by conducting tensile tests on universal testing machine.

3.2 Preparation of the alloys

Al–Si alloys with varying Si percentage were prepared by melting commercially pure aluminium (99.7%) and commercially pure silicon (99.5%) in a graphite crucible in a high frequency induction furnace and the melt was held at 720 °C in order to attain homogeneous composition. After degassing with 1% solid hexachloroethane, 0.1% Al–Ti master alloy was added to the melt for modification of microstructure. Each melt was stirred for 30s after the addition of the modifier, held for 5 min and then poured into a cubical graphite mould surrounded by fireclay bricks. The cast samples were of 100 mm length, 30 mm wide and 20 mm height.

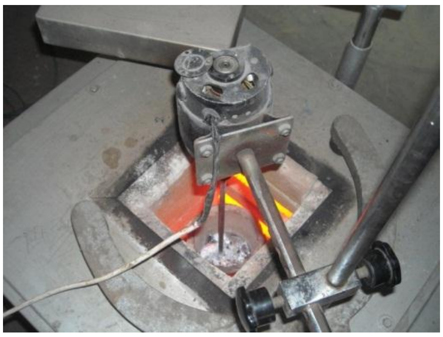

Fig 3.1 Laboratory stir casting set up

The following table 3.1 shows the weight of Al and Si taken, in grams, for the preparation of Al-7% Si, Al-12% Si and Al-14% Si alloys.

Table 3.1 Composition of Al-Si alloys

Sl.No.	Material	Al (in gms)	Si (in gms)
1	Al - 7% Si	250	18.8
2	Al - 12% Si	250	34.1
3	Al - 14% Si	250	40.7

3.3 Optical Emission Spectrometer

The chemical compositions of the cast alloys were evaluated using optical emission spectrometer (Model: ARL 3460 Metals Analyser, Thermo Electron Corporation Limited, Massachusetts, United States of America). The samples were cylindrical shape of 20 mm diameter and 10 mm height. Here, excitation is done by an arc or a spark and the analysis of the spectrum of frequencies of emitted electromagnetic radiation is done to identify the elements.

3.4 Scanning Electron Microscopy

Microstructural characterization studies were done to observe the microstructure of sample surface and also the surface after wear test. This is done by using scanning electron microscope. The Al-Si samples of different weight composition were mechanically polished using standard metallographic techniques before the examination. Characterization is done in etched conditions. Etching was done using the Keller’s reagent (1 volume part of hydrofluoric acid (48%), 1.5 volume part of hydrochloric acid, 2.5 volume parts of nitric acid and 95 volume parts of water). The SEM micrographs of the samples were obtained. The images were taken in secondary electron (SE) mode. This analysis was done by a scanning electron microscope equipped with Energy Dispersive X-Ray Spectroscopy (EDS) (Model: JEOL 6480 LV scanning electron microscope, JEOL Limited, Japan).

Figure 3.2 JEOL JSM-6480LV scanning electron microscope

3.5 Optical Microscopy

Microstructures of the alloy samples were observed under computerized optical microscope (Model: Olympus BX51, Essex, UK). The Al-Si samples of different weight composition were mechanically polished using standard metallographic techniques before the examination. Characterization is done in etched conditions. Etching was done using the Keller's reagent (1 volume part of hydrofluoric acid (48%), 1.5 volume part of hydrochloric acid, 2.5 volume parts of nitric acid and 95 volume parts of water). The micrographs of the samples were obtained.

Fig 3.3 Computerized Optical Microscope

3.6 Tensile test

Tensile properties of the alloys were analysed by carrying out test on the universal testing machine (Model: INSTRON 1195, Instron Industrial Products, Pennsylvania, USA). Tensile tests were carried out with a crosshead speed of 1mm/min, which corresponds to nominal strain rate of 0.001 per second. During the tests, the load elongation data is captured by induced software, whose data is used for further analysis. The figure 3.4 shows the dimensions for the specimen for this test. The numbers shown are the lengths in mm.

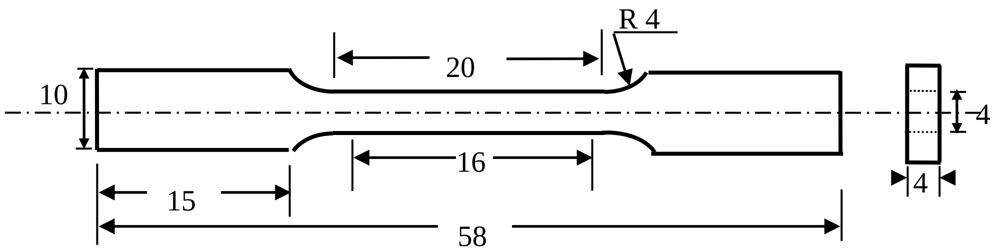

Fig 3.4 Tensile test specimen

Fig 3.5 Universal testing machine, INSTRON

3.7 Vickers Hardness Test

The macrohardness tests of all the samples have been done using a Vicker's hardness testing machine. The applied load during the testing was 5 kgf, with a dwell time of 15 s. It has a square-base diamond pyramid indenter. The Vickers hardness number (VHN) is calculated from the following equation:

$$VHN = \frac{1.854\,P}{D^2}$$

where P = applied load, kgf

D = average length of diagonals, mm

Fig 3.6 Vickers hardness testing machine

3.8 Wear test

Computerized Ducom friction and wear monitor pin on disc wear test machine was used for the wear tests (Model: DUCOM Wear and Friction Monitor, TR-20-M100, Bangalore, India). The rotating disc was made of carbon steel of diameter 50 mm and hardness of 64 HRC. The Al-7%Si, Al-12%Si and Al-14%Si samples were held stationary and a required normal load was applied through a lever mechanism. The tests were carried out by varying one of the following three parameters and keeping other two constants:

i. applied load (is 20 N, when constant)

ii. sliding speed (is 20 rpm, when constant)

iii. sliding distance (is 1256 m, when constant)

No lubricant is used as test is carried out in dry conditions. Care has been taken that the specimens under test are continuously cleaned with woollen cloth to avoid the entrapment of wear debris and to achieve uniformly in experiential procedure. Scanning electron microscopy was used to analyse the morphology of the worn surfaces of sample.

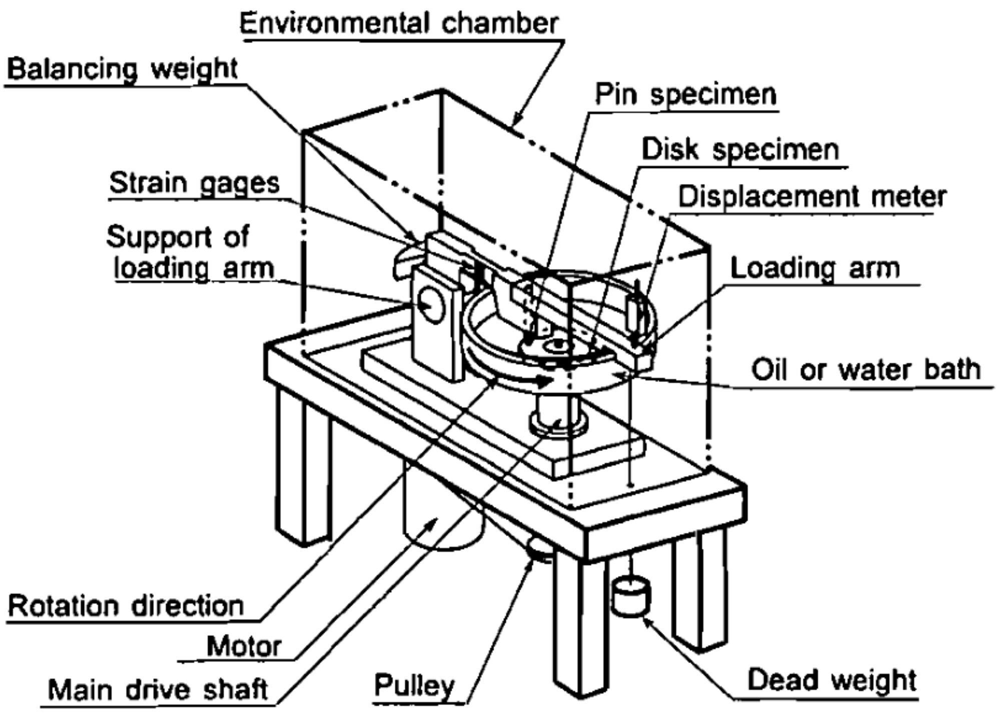

Fig 3.7 Pin-on-disk type friction and wear apparatus[16]

Fig 3.8 Ducom friction and wear monitor pin on disc wear test machine

Fig 3.9 Full view of Ducom friction and wear monitor

CHAPTER – 4

RESULTS AND DISCUSSION

4.1 Introduction

Different tests like compositional analysis, tensile test, macrohardness test, wear test etc. on Al-Si alloys were carried out. The results obtained from these tests are reported, analysed and discussed further in this chapter.

4.2 Compositional Analysis

The following table 4.1 shows the weight percentage of different elements present in the prepared Al-Si samples.

Table 4.1 Weight percentage of different elements present in the Al-Si samples

	Al-7% Si (wt%)	**Al-12% Si (wt%)**	**Al-14% Si (wt%)**
Si	7.003	12.002	13.76
Fe	0.157	0.151	0.14
Cu	0.007	0.003	0.005
Mn	0.008	0.009	0.007
Mg	0.001	-	-
Zn	0.038	0.022	0.019
Ti	0.016	0.011	0.018
Ni	0.002	-	-
Ca	0.003	0.003	0.001
B	0.001	0.002	0.001
Bi	-	0.001	-
V	0.004	0.004	0.004
Co	0.001	0.001	0.001
Sb	0.001	0.001	0.001
Ga	0.015	0.015	0.015
P	0.001	-	-
As	0.002	0.002	0.002
Al	92.74	87.77	86.02

4.2.1 Discussion

The weight percentage of silicon in Al-7% Si and Al-12% Si is found to be 7.003% and 12.002% which is very close to 7% and 12% respectively. This suggests that the cast structure made is very sound. It can be seen that there is no loss of silicon and aluminium evaporation. The weight percentage of silicon in Al-14% Si is found to be 13.76% which is still close to 14%. This may be due to some loss of silicon.

4.3 Microstructure

Microstructures obtained from computerised optical microscope are shown in fig 4.13 to fig 4.15 for Al-7% Si, Al-12% Si and Al-14% Si respectively.

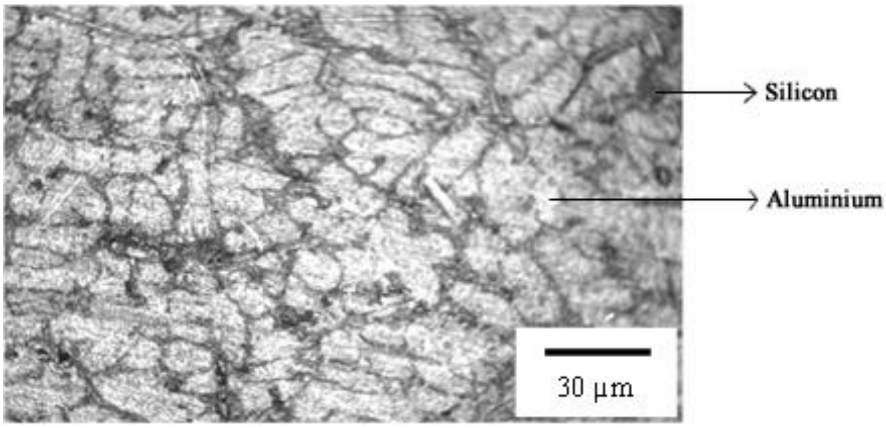

Fig 4.1 Microstructure of Al-7% Si sample

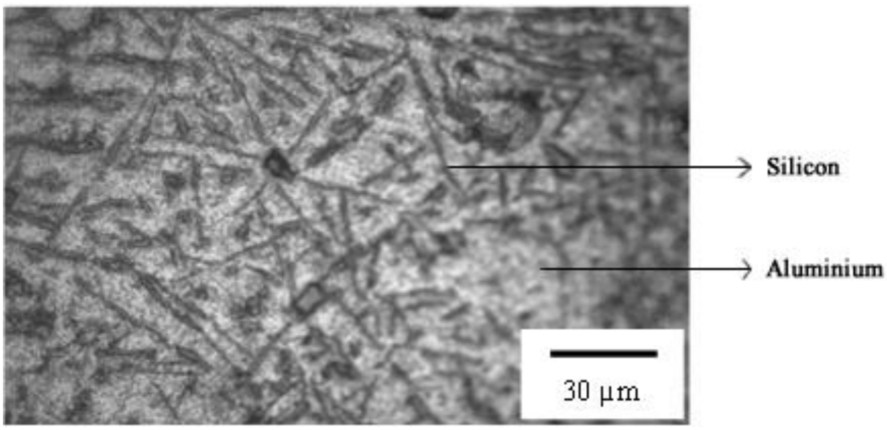

Fig 4.2 Microstructure of Al-12% Si sample

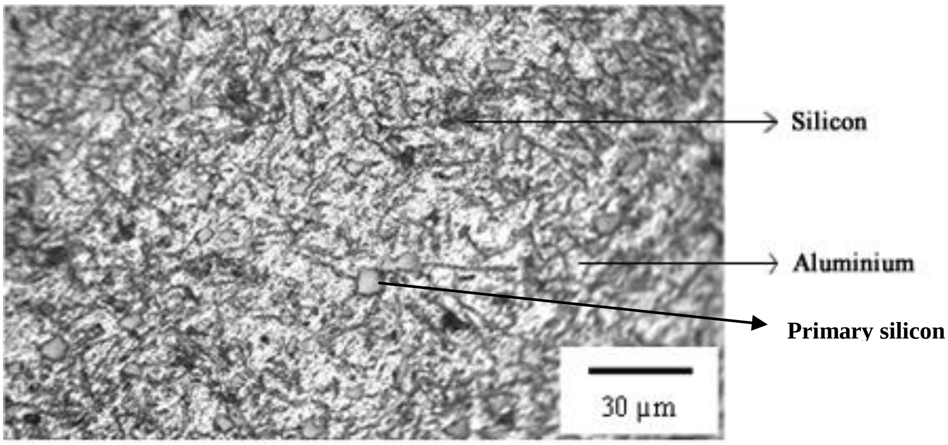

Fig 4.3 Microstructure of Al-14% Si sample

4.3.1 Discussion

Figure 4.1 shows an optical micrograph of Al-7% Si alloy and it may be seen that more-or-less rounded particles of aluminium (light areas, α-solid solution) are crystallized, which are surrounded by fine eutectic silicon (dark areas). Here, silicon has networked structure. The micrograph of Al-12% Si alloy in Fig. 4.2 shows the refinement of the eutectic silicon particles. The silicon has long rod like structure. It may be seen in Fig. 4.3 that the degree of refinement of the eutectic silicon increased as the silicon content of the alloy increased beyond the eutectic composition. Here the primary silicon appears as coarse polyhedral particles. In addition, presence of primary silicon is also observed in the Al-12% Si and Al-14% Si alloys, although the size and volume fraction of the primary silicon is more in Al-14% Si, as compared to Al-12% Si alloys.

4.4 Tensile Test

From the load and elongation values, obtained from the universal testing machine, corresponding engineering stress and engineering strain were calculated and plotted to get stress vs. strain curves for different samples of Al-7% Si, Al-12% Si and Al-14% Si alloys.

4.4.1 For Al-7% Si:

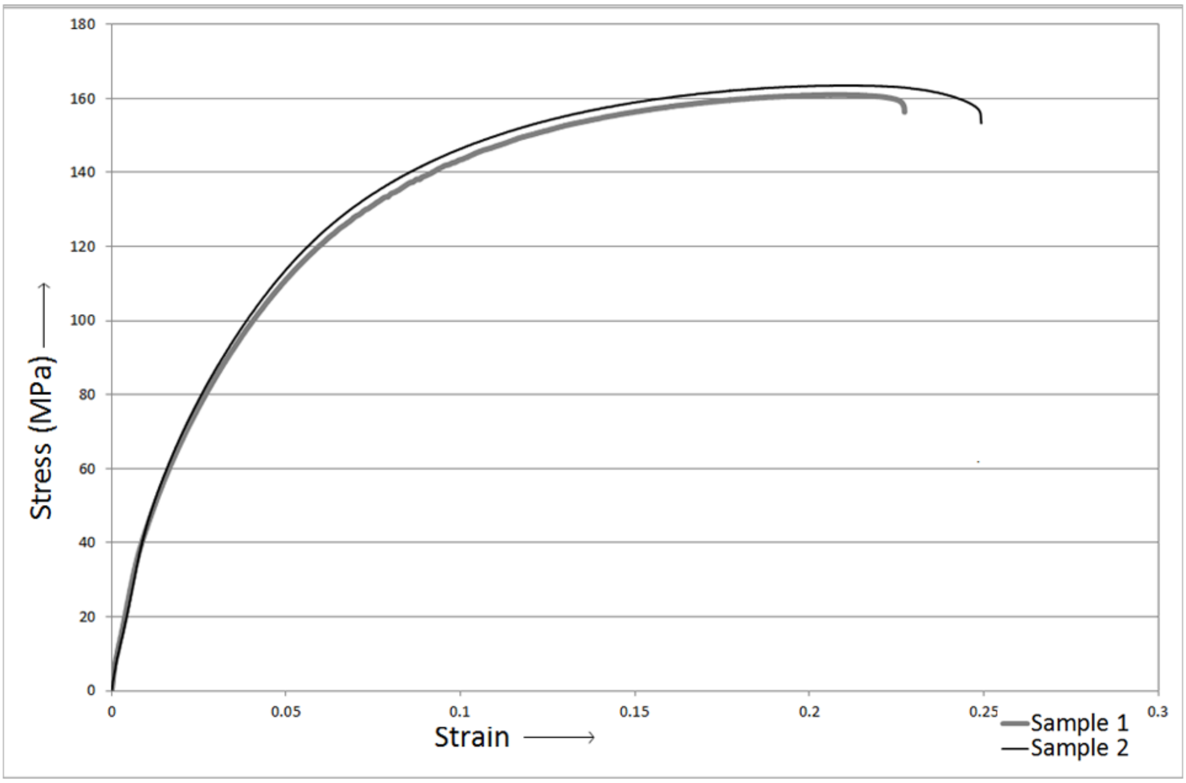

Fig 4.4 Engineering stress – strain curve for Al-7% Si samples

The ultimate tensile strength and total elongation for the first sample of Al-7% Si were found to be 160.97 MPa and 22.72 % respectively. The yield strength was calculated to be 41.3 MPa.

The ultimate tensile strength and total elongation for the second sample of Al-7% Si were found to be 161.87 MPa and 24.912 % respectively. The yield strength was calculated to be 45.5 MPa.

4.4.2 For Al-12% Si:

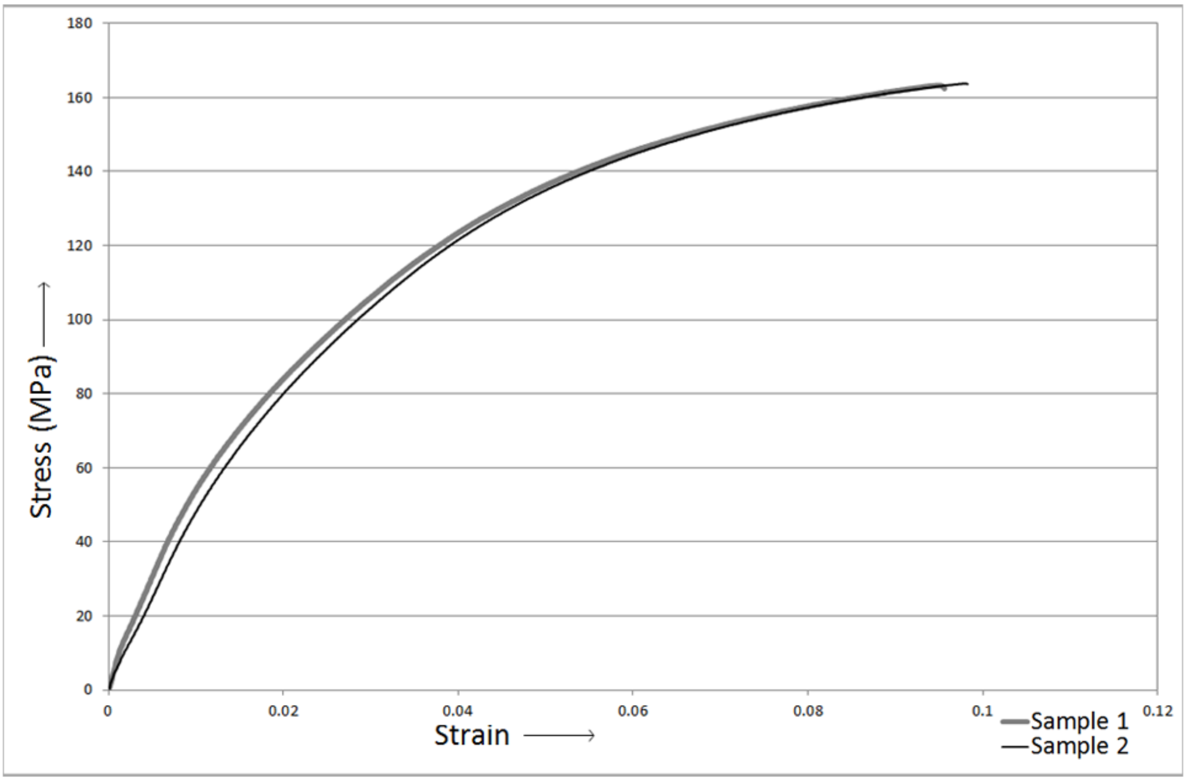

Fig 4.5 Engineering stress – strain curve for Al-12% Si samples

The ultimate tensile strength and total elongation for the first sample of Al-12% Si were found to be 163.21 MPa and 9.544 % respectively. The yield strength was calculated to be 48.7 MPa.

The ultimate tensile strength and total elongation for the second sample of Al-12% Si were found to be 163.71 MPa and 9.816 % respectively. The yield strength was calculated to be 50.6 MPa.

4.4.3 For Al-14% Si:

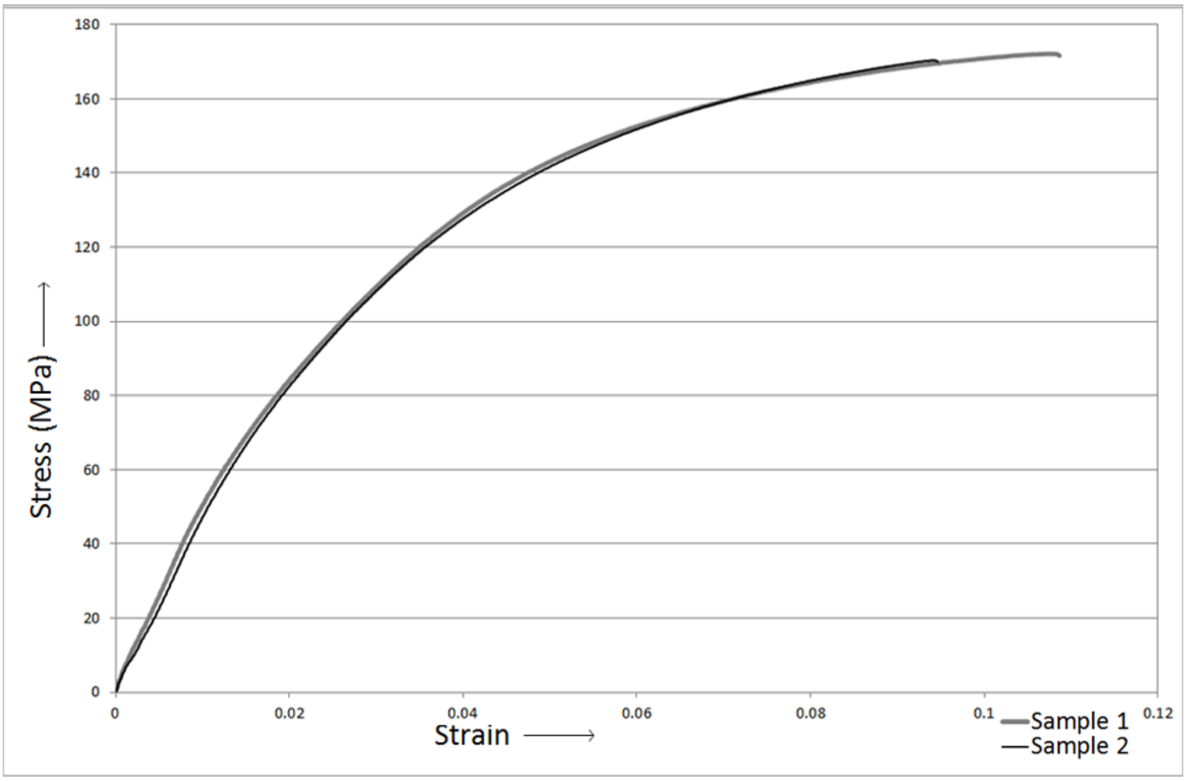

Fig 4.6 Engineering stress – strain curve for Al-14% Si samples

The ultimate tensile strength and total elongation for the first sample of Al-14% Si were found to be 172.13 MPa and 10.848 % respectively. The yield strength was calculated to be 61 MPa.

The ultimate tensile strength and total elongation for the second sample of Al-14% Si were found to be 170.38 MPa and 9.448 % respectively. The yield strength was calculated to be 62.5 MPa.

4.4.4 Comparison of Ultimate Tensile Strength:

The following table 4.2 shows the values of ultimate tensile strength (in MPa) for Al-7% Si, Al-12% Si and Al-14% Si; and the corresponding histogram is shown in Fig. 4.7.

Table 4.2 Ultimate tensile strength (in MPa) of Al-Si alloys

	UTS of Sample 1 (In MPa)	UTS of Sample 2 (In MPa)	Average UTS (In MPa)
Al - 7% Si	160.97	161.87	161.42
Al – 12% Si	163.21	163.71	163.46
Al – 14% Si	172.13	170.38	171.255

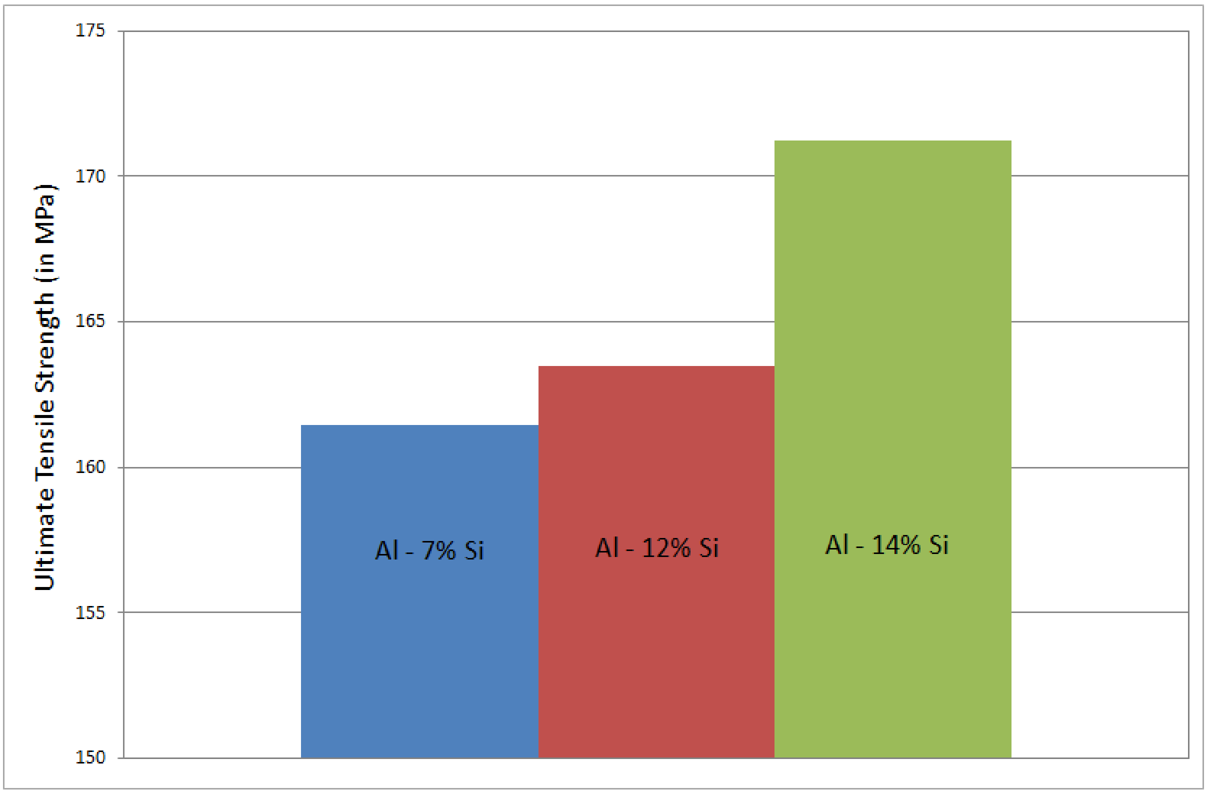

Fig 4.7 Histogram showing values of UTS for different Al-Si alloys

4.4.5 Comparison of Yield Strength:

The following table 4.3 shows the values of yield strength (in MPa) for Al-7% Si, Al-12% Si and Al-14% Si; and the corresponding histogram is shown in Fig. 4.8.

Table 4.3 Yield strength (in MPa) of Al-Si alloys

	YS of Sample 1 (In MPa)	YS of Sample 2 (In MPa)	Average YS (In MPa)
Al - 7% Si	41.3	45.5	43.4
Al – 12% Si	48.7	50.6	49.65
Al – 14% Si	61	62.5	61.75

Fig 4.8 Histogram showing values of YS for different Al-Si alloys

4.4.6 Comparison of Total Elongation:

The following table 4.4 shows the values of total elongation (in %) for Al-7% Si, Al-12% Si and Al-14% Si; and the corresponding histogram is shown in Fig. 4.9.

Table 4.4 Total elongation (in %) of Al-Si alloys

	Total Elongation of Sample 1 (In %)	Total Elongation of Sample 2 (In %)	Average Total Elongation (In %)
Al - 7% Si	22.72	24.912	22.816
Al – 12% Si	9.544	9.816	9.68
Al – 14% Si	10.848	9.448	10.418

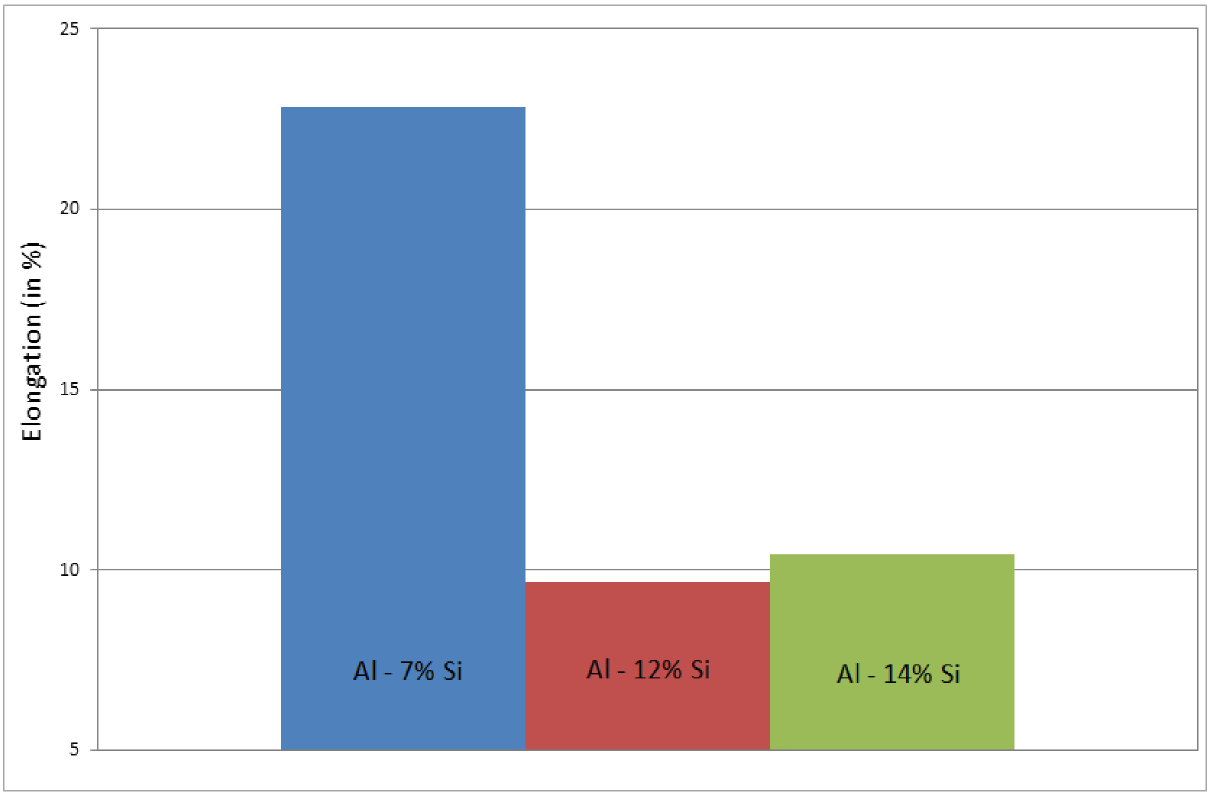

Fig 4.9 Histogram showing values of total elongation for different Al-Si alloys

4.4.7 Discussion:

From Fig. 4.4 to Fig. 4.6, it can be observed that the curves are continuous when transition from elastic to plastic region takes place. Therefore, the yield strengths of the alloys are computed by 0.2% offset method, according to ASTM standard E8M[17]. From Fig. 4.7 and Fig. 4.8, it is observed that ultimate tensile strength and yield strength increases with the increase of weight percentage of silicon; while it is reverse for the total elongation. This may be due to the presence of hard silicon precipitates which increases the hardness of Al-Si alloys.

4.5 Vickers Hardness Test

The macrohardness tests of all the samples were conducted using a Vicker's hardness testing machine with a dwell time of 15 s and applied load of 5 kgf (P) during the tests. For each composition, five indentations were taken and average value is reported. The following table shows the lengths of the diagonals of the impression on the surface and the calculated Vickers hardness number (VHN).

Table 4.5 Vickers hardness number of different Al-Si alloys

Composition	D_1 (in µm)	D_2 (in µm)	VHN	Avg VHN
Al-7% Si	431.6	430.5	49.9	52.14
	421.5	416.6	52.8	
	425.6	418.3	52.1	
	418.7	415.9	53.2	
	421.3	417.6	52.7	
Al-12% Si	371.8	375.0	66.5	65.5
	369.4	386.4	64.9	
	376.9	378.8	64.9	
	373.6	375.8	66.0	
	376.3	378.1	65.2	
Al-14% Si	367.3	370.4	68.2	69.12
	359.3	362.9	71.1	
	362.4	365.3	70.0	
	369.7	367.8	68.2	
	368.9	369.1	68.1	

Figure 4.10 shows the variation of Vickers hardness number of Al-7% Si, Al-12% Si and Al-14% Si with silicon percentage.

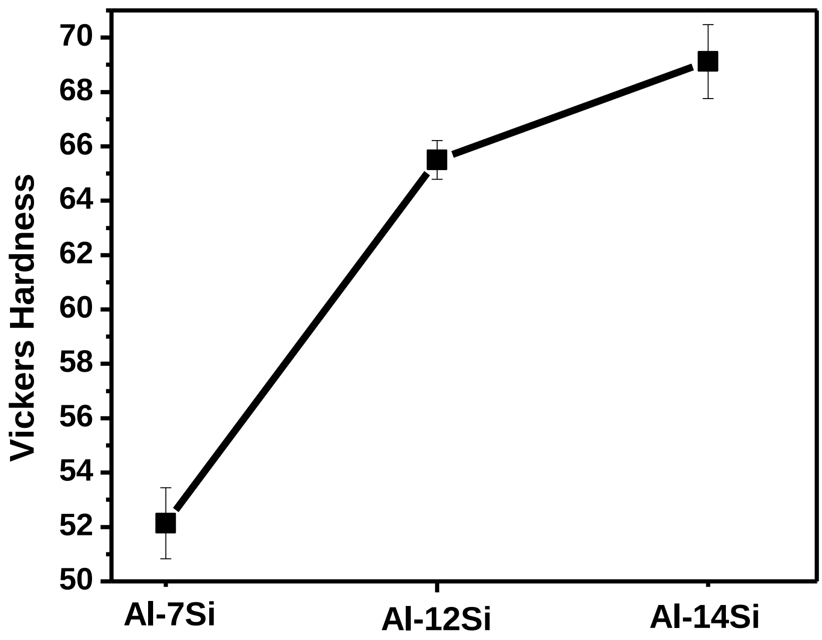

Fig 4.10 Variation of hardness along with their standard deviation

4.5.1 Discussion:

The Vickers hardness numbers for Al-7% Si, Al-12% Si and Al-14% Si are found to be 52.14, 65.5 and 69.12 respectively. This shows that hardness of the Al-Si alloy increases with the increase in the weight percentage of silicon. This may be due to the increment of silicon amount, which is harder.

4.6 Wear Test

The wear tests of Al-Si alloys were carried out with varying applied load, sliding speed and sliding distance. The results are obtained from the series of tests which is done by keeping two parameters out of the three (sliding distance, sliding speed and load) constant against wear.

i. Load vs. wear

ii. Sliding speed vs. wear

iii. Sliding distance vs. wear

The results from the above tests are noted and corresponding curves are drawn as shown in the next pages.

4.6.1 Load vs. Wear

Table 4.6 Experimental values of wear of Al-Si alloys at different applied loads

	Load (kN)	Wear (µm)		
		Al – 7% Si	Al – 12% Si	Al – 14% Si
Sample I	10	83.45	35.44	19.29
Sample II	20	108.79	50.5	35.13
Sample III	30	155.44	107.77	74.88

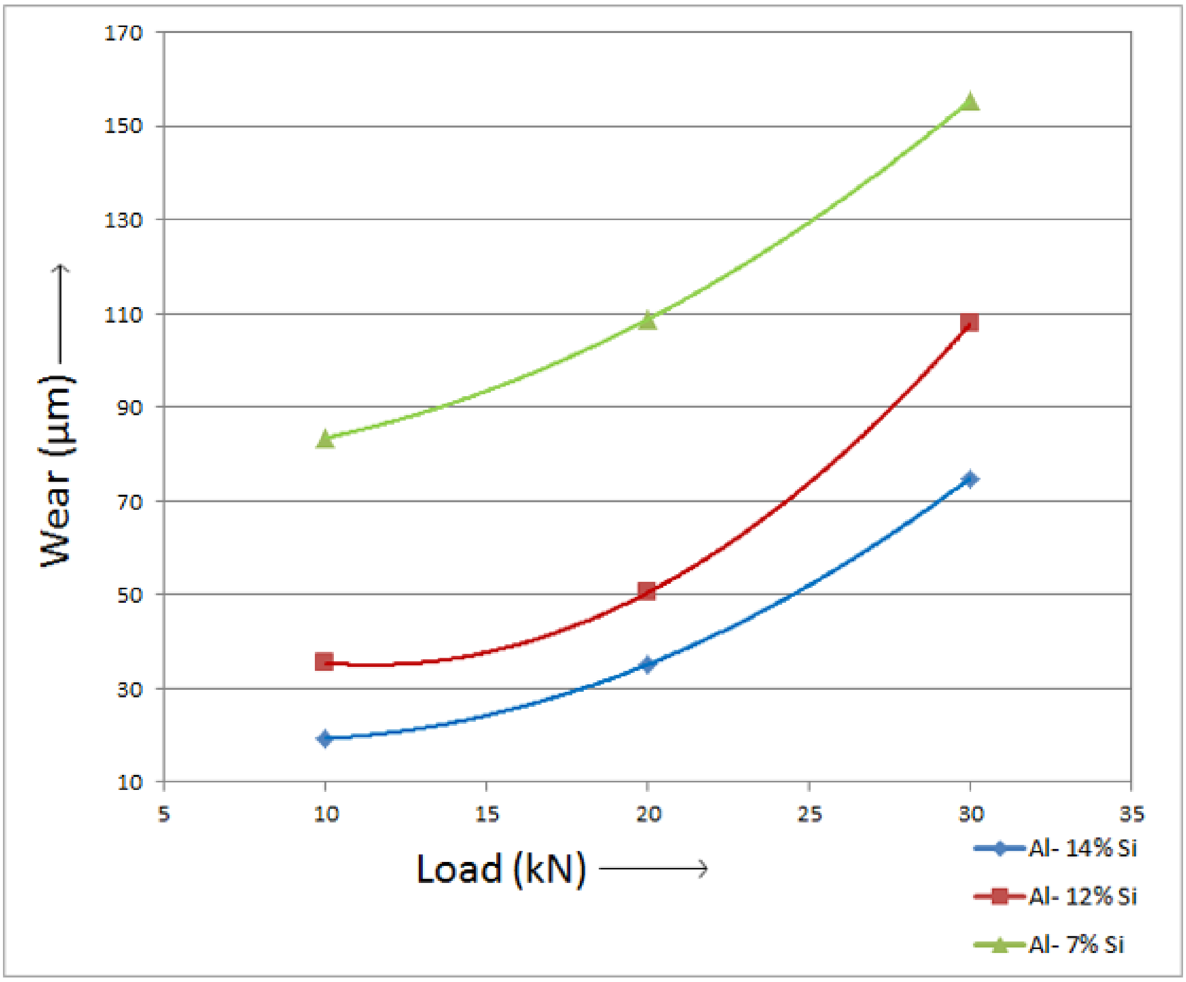

Fig 4.11 Variation of wear of Al-Si alloys with load

4.6.2 Sliding speed vs. Wear

Table 4.7 Experimental values of wear of Al-Si alloys at different sliding speeds

	Sliding Speed (rpm)	**Wear (µm)**		
		Al – 7% Si	**Al – 12% Si**	**Al – 14% Si**
Sample I	10	64.44	50.5	37.55
Sample II	20	86.62	69.77	60.48
ample III	30	124.11	114.74	100.79

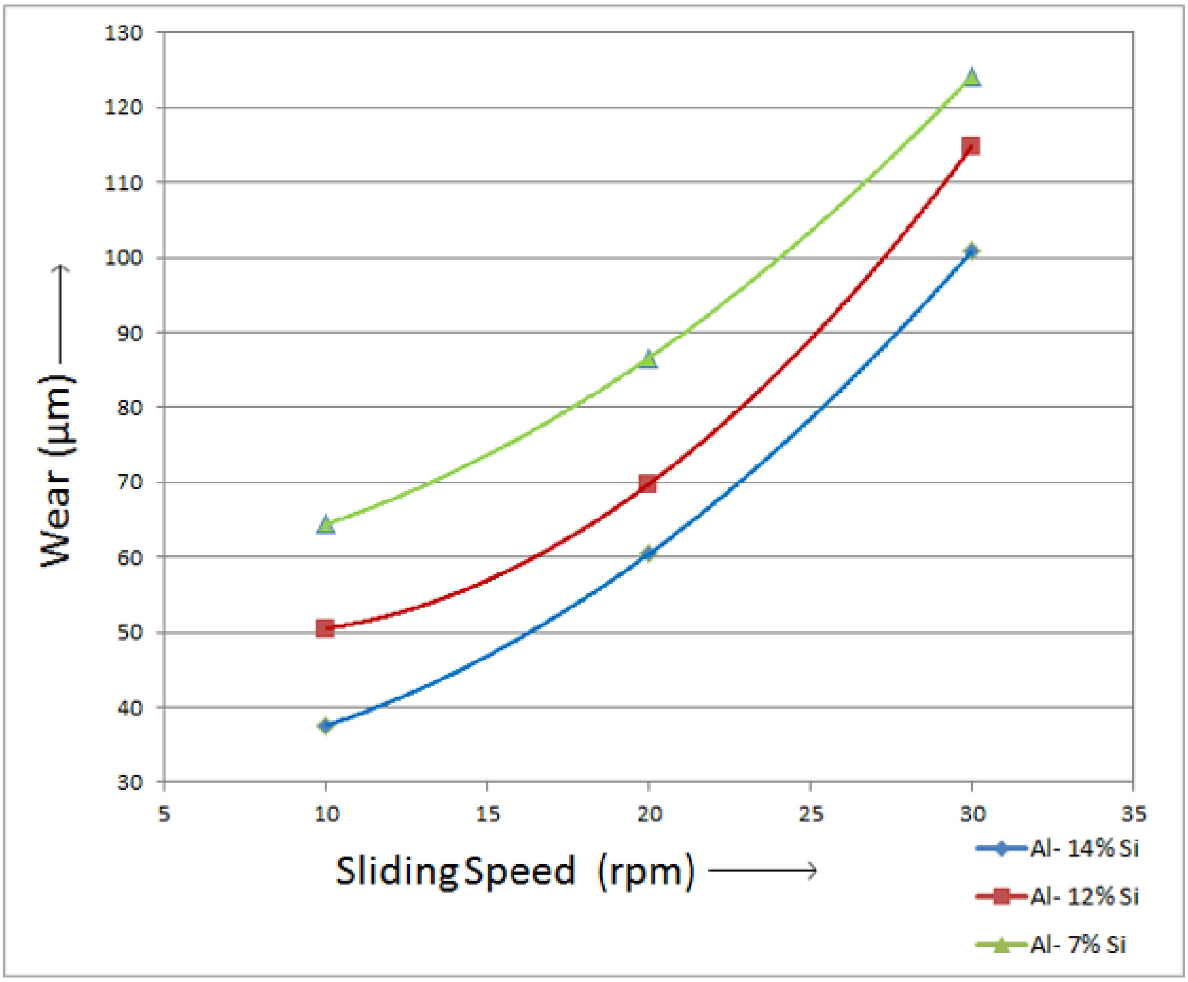

Fig 4.12 Variation of wear of Al-Si alloys with sliding speed

4.6.3 Sliding Distance vs. Wear

Table 4.8 Experimental values of wear of Al-Si alloys at different sliding distances

	Sliding Distance (mm)	Wear (µm)		
		Al – 7% Si	Al – 12% Si	Al – 14% Si
Sample I	1256	135.58	124.38	117.48
Sample II	1884	152	141.21	135.06
Sample III	2512	198.42	182.43	163.51

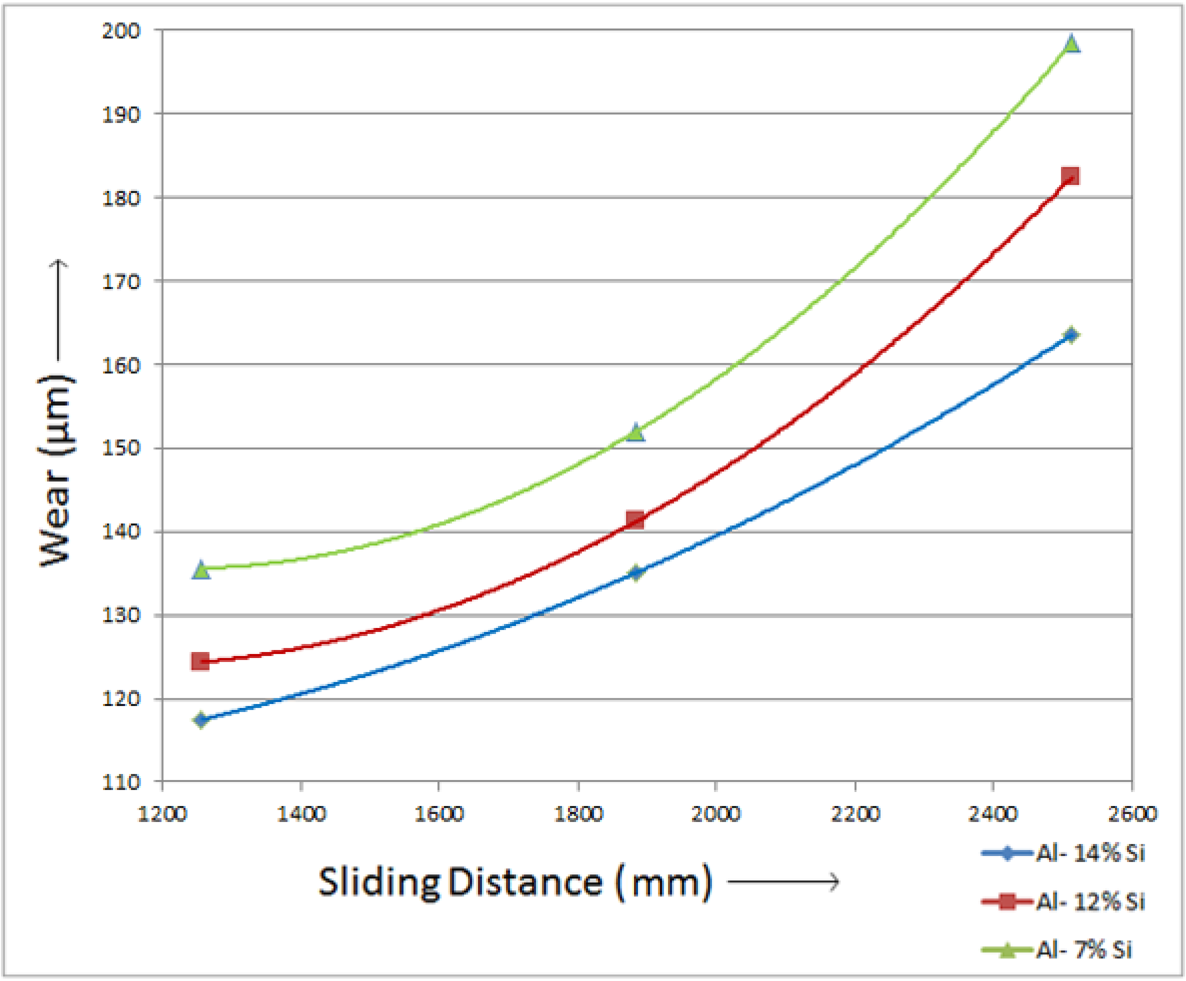

Fig 4.13 Variation of wear of Al-Si alloys with sliding distance

4.6.4 Discussion

The results of wear tests on all samples with varying loads (10, 20, 30 N) are given in Table 4.6 and the behaviour is illustrated in Fig. 4.11. It is noticed that the height loss due to wear decreases when the percentage of silicon increases. For Al-7% Si alloy, the height loss is 83.45 μm, whereas for Al-12% Si alloy, the height loss was decreased to 35.44 μm and for Al-14% Si alloy, the height loss is only 19.29 μm for 10 N load. Similar trends in height loss for all other loads is observed. The decrease in height loss with increasing percentage of silicon can be attributed to the presence of hard silicon particles adhered to the alloy.

Variation of sliding speed with wear is shown in Fig. 4.12. With the increase in sliding speed, the interface temperature of the sample increases making it more soft and thus increases the height loss. For Al-7% Si alloy, the height loss is 64.44 μm, whereas for Al-12% Si alloy, the height loss was decreased to 50.5 μm and for Al-14% Si alloy, the height loss is only 37.55 μm for 10 rpm sliding speed. Similar trends in height loss for 20 rpm and 30 rpm sliding speeds is observed.

With the increase in sliding distance, height loss increases due to more amount of time in wearing. Here also, similar to previous cases, height loss is highest in Al-7% Si alloy and lowest in Al-14% Si alloy, which is due to the presence of hard silicon particles.

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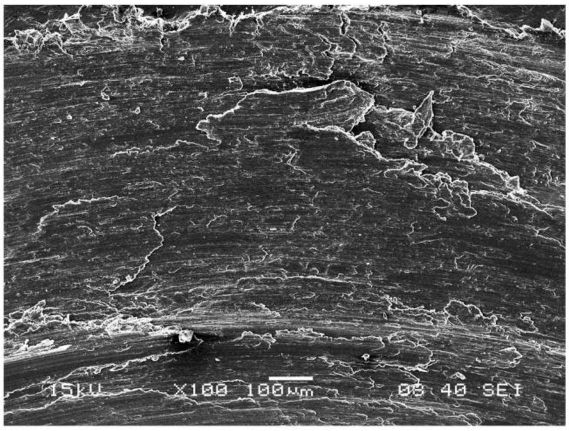
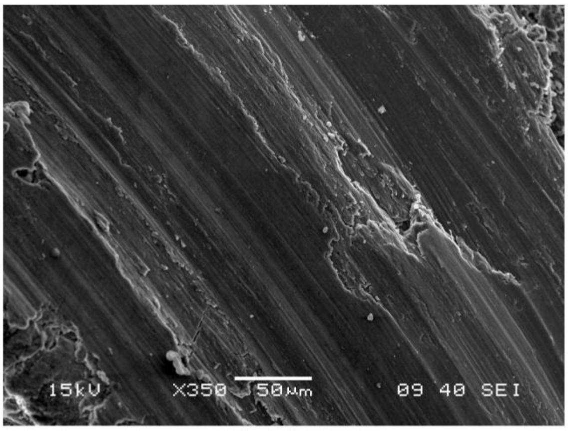
4.6.5 *Microstructure of worn surface*

The alloy samples from the wear test with load 20 N, sliding speed 20 rpm and sliding distance 1256 m are taken and their worn surfaces are observed with scanning electron microscope. Following Fig. 4.14 and Fig.4.15 show the micrographs taken at low and high magnifications respectively.

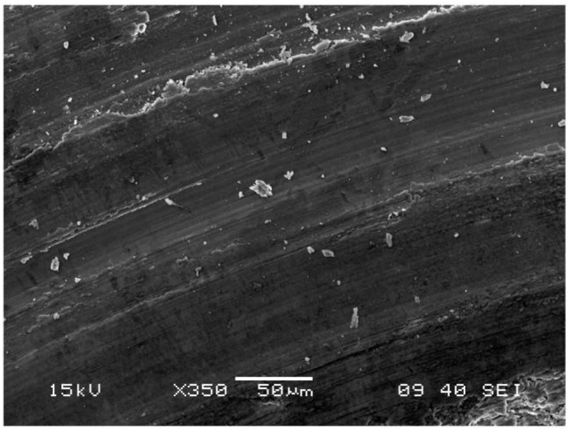
Worn surfaces at low magnification:



a. Al-7% Si



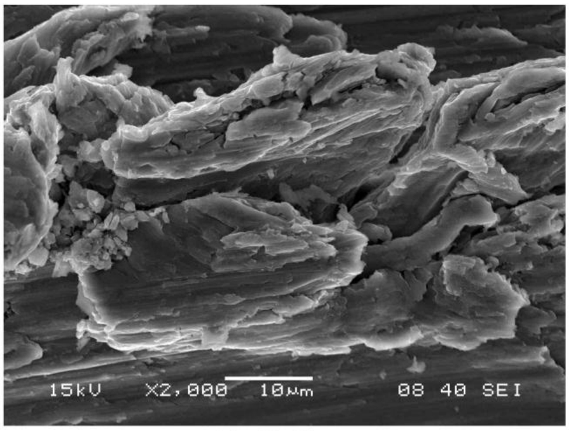
b. Al-12% Si



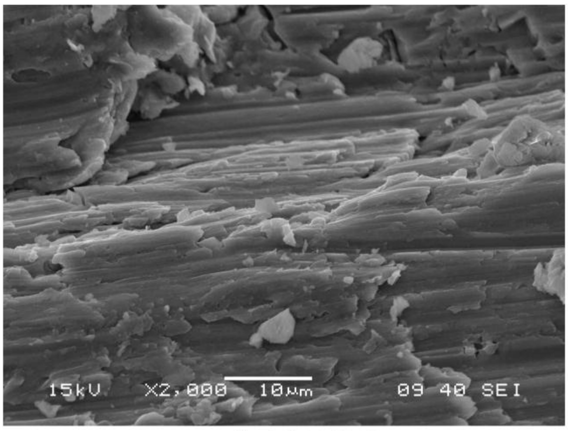
c. Al-14% Si

Fig 4.14 Microstructure of Al-Si samples at low magnification

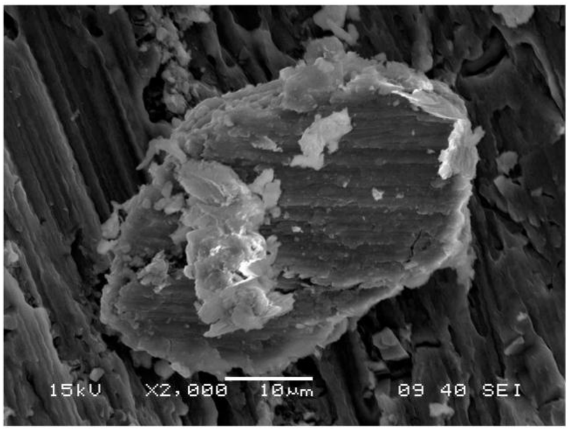
Worn surfaces at high magnification:



a. Al-7% Si



b. Al-12% Si



c. Al-14% Si

Fig 4.15 Microstructure of Al-Si samples at high magnification

4.6.6 Discussion

The worn surfaces of the samples were examined under SEM to investigate the wear mechanism. The low magnification SEM micrographs, Fig. 4.14, show fine scoring marks. The scoring depth in case of Al-7% Si alloy is more as compared to Al-12% Si and is lowest in Al-14% Si. It indicates wear is highest in Al-7% Si and lowest in Al-14% Si. The presence of scoring marks may be due to abrasion by entrapped debris, hard asperities on the hardened steel counter face or work hardened deposits on the counter face[18]. The high magnification SEM micrographs, Fig. 4.15, show the evidence of extensive plastic flow and cracking. It is also possible that the hard dispersoid particles or fractured pieces are mechanically dislodged during wear. The pinholes so formed act as potential sites for nucleation and growth of cracks. When cracks grow and get interconnected, a layer of metal gets removed[19].

CHAPTER – 5

CONCLUSION

The conclusions drawn from the conducted investigations are as follows:

1. The prepared aluminium-silicon alloys have homogenous distribution of silicon throughout the cast.
2. The amount of primary silicon increases with the increase in silicon amount in the cast.
3. Yield strength and ultimate tensile strength increases with the increase of weight percentage of silicon.
4. Total elongation decreases with the increase of weight percentage of silicon.
5. Hardness of the Al-Si composite increases with the increase in amount of silicon present.
6. The height loss due to wear decreases when the percentage of silicon increases.

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