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Study of Mechanical and Tribological Properties of Al-Si alloy Prepared by Powder Metallurgical technology

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Abstract: *Aluminium alloys have extensive application in industries. The range of physical properties that can be imparted to them is remarkable. Mixing of Silicon to aluminium tends to increase its strength to weight ratio and wear resistance, and tends to decrease its density and coefficient of thermal expansion. In the present work Al-Si alloy cylindrical pin is produced through powder metallurgy process and experimentation is made to determine the mechanical & tribological properties of five alloy samples i.e. Al-9wt%Si, Al-12wt%Si, Al-14wt%Si Al-17wt%Si and Al-21wt%Si.A composition analysis is done in the testing laboratory to verify the weight% of Silicon & Aluminium in the Al-Si alloy. Density test is done by measuring mass & volume of the alloy samples. Hardness of the alloy samples is measured by taking four indentations with the help of Brinell hardness testing machine and calculating its hardness number. Porosity of the samples is evaluated by considering the density of the sintered component (γp) &the density of the solid alloy material (γs). Wear tests is conducted using a pin on-disc type wear testing machine (DUCOM wear and friction monitor) and taking sliding velocity and applied load as the parameters.*
keywords: *Aluminium; Silicon; powder metallurgy; Hardness; Wear; Fractional Porosity; Sliding Velocity;*

I. Introduction

Aluminium (Al) is the second most plentiful element on earth and it emerged as an economic competitor in the engineering applications as early as in the end of the 19th century. The emergence of three industrial revolutions saw the emergence of aluminium and its alloys as one of the most demanded raw materials in the industrial world. 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 in various automobile industries. Thus it becomes all the more vital to study the tribological characteristics of aluminium and its alloys [1].

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 [2].

Table 1.1 Designation of aluminium alloys and their applications.

Alloys	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	
9xxx	Unassigned	

Addition of Silicon to aluminium gives high strength to weight ratio, low thermal expansion co-efficient and high wear resistance. These alloys show improved strength and wear properties as the silicon content is increased beyond eutectic composition. Such properties warrant the use of these materials as structural components in automotive industries. Silicon also 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 [3]

Many Researchers have worked out on different aspects of Al-Si or other alloy. They also studied about the tribological and other behaviors. In this work, five Al-Si alloy cylindrical pins are produced using powder metallurgy with different compositions (i.e. Al-9wt%Si, Al-12wt%Si, Al-14wt%Si Al-17wt%Si and Al-21wt%Si) and their properties are studied. The properties that are considered in this paper arevariation of density of alloy-samples, fractional porosity of the alloy-samples, hardness number of different p/m alloy samples, wear behavior of the alloy samples, wt.% of Aluminium and Silicon in different samples after all tests are over.

II. Aluminium Silicon Alloys

Alloys of Aluminium 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. 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. 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, low specific gravity and superior tribological characteristics compared to the other aluminium alloys. These alloys have been successfully used as substitute for cast iron in applications such as pistons and cylinder linings for internal combustion engines, connecting rods and sockets in refrigerant compressors. Although casting of these alloys are somewhat more difficult to machine than the aluminium-copper or aluminium-magnesium alloys, all type of machining operations are routinely accomplished, usually using tungsten carbide tools and appropriate coolants and lubricants.

2.1 Hypoeutectic, Eutectic and Hypereutectic Aluminium-Silicon alloys

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 , 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%.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).[4]

It is known that increasing the Si content results in an increase of the strength of hypoeutecticalloys and a decrease of the strength of hypereutectic alloys[5,6].

III. Preparation Of Al-Si Alloy Pin

3.1 Weight measurement of powder

5 samples of Al-Si alloy are prepared. The following table shows weight of elemental-compositions taken in grams, in five different Al-Si p/m alloy samples for the preparation of alloy **P**: Al-9%Si, alloy **Q**: Al-12%Si,alloy **R**: Al-14%Si,alloy **S**: Al-17%Si and alloy **T**: Al-21%Si.

Table 1 Composition of Al-Si Alloy

	Alloy P	Alloy Q	Alloy R	Alloy S	Alloy T
Composition	Wt. (gms)	Wt. (gms)	Wt. (gms)	Wt. (gms)	Wt. (gms)
Si	9	12	14	17	21
Cu	1.3	1.3	1.3	1.3	1.3
Cr	0.1	0.1	0.1	0.1	0.1
Fe	1.0	1.0	1.0	1.0	1.0
Mg	1.0	1.0	1.0	1.0	1.0
Ni	1.3	1.3	1.3	1.3	1.3
Zn	0.25	0.25	0.25	0.25	0.25
Ti	0.05	0.05	0.05	0.05	0.05
Al	86	83	81	78	74
Total	100	100	100	100	100

3.2Mixing of powders

Here ball milling type mixing method is adopted for proper mixing. The powder of each sample is kept in a cylindrical steel container of 55 mm diameter and 78 mm length. In the above container containing powder mix, 24 numbers of spherical steel balls (bicycle ball bearing) are put. Then the closed container is rotated at 160 rpm in both clock wise and anti-clockwise direction for 30 minutes each. Steel balls are removed and the Powder is weighed in the digital weighing machine. The balls were rotated by holding it in a lathe chuck.

3.3 Die preparation

12 mm diameter circular cross section die and punch set is made for compacting circular pin. Another die of 30 mm. dia. is made for holding the 12 mm. diameter die. The length of both the dies are 80 mm. Lower punch, upper punch and hollow cylindrical rod are 25 mm, 38 mm and 28 cm long respectively. The die sets are made of high strength tool steel (EN-8) with a highly polished die cavity. The clearance between die and punch is maintained as 0.1mm.

3.4 Compaction of powder

Compaction of different powders is done in the universal testing m/c at different compaction pressures with the help of prepared die and punch. The corresponding pressures of compaction for Al-Si alloys are mentioned below.

Table 2: Compaction Pressures for different alloy samples.

Alloys	Alloy composition	Compaction Pressure(KN)
Alloy-P	Al-9%Si	70
Alloy-Q	Al-12%Si	76
Alloy-R	Al-14%Si	81
Alloy-S	Al-17%Si	85
Alloy-T	Al-21%Si	95

3.5 Sintering of Green Compact

Sintering of the green compact of the 5 alloys is done in the vacuum furnace at 520°C.

Table 3: Steps in sintering operation

Segment -1	Compacts heated to 400°C starting from room temperature. Heating rate should be less than 4°C per minute to reduce stress in the compact.
Segment -2	Green compacts are heated to 520° C starting from 40° C. Here heating rate should be less than 3.5°C per minute to eliminate danger of thermal Cracks in compacts.
Segment -3	Temperature is held at 520°C for half an hour to complete chemical and diffusion activities.

3.6 Heat Treatment process

The Heat treatment process is carried out in vacuum furnace. The process is controlled by programming through PID controller. The programming is done in three segments, for temperature up to 500°C. After execution of the programme, the temperature is raised manually up to 800°C.Then the furnace temperature is lowered and the samples are allowed to cool.

IV. Determination Of Mechanical Properties Of Al-Si Alloy Pin

4.1 Density measurement

Two samples from each type of alloy are taken for density calculation. The functional parameters diameter (d) and length (l) are measured by vernier caliper. Mean diameter (dm) and mean length (lm) of each sample are obtained. Volume of each sample is calculated.Alloy samples are weighed by Digital Weighing Machine and Mean Mass (Mm) is calculatedfor each sample.Densities (ρ) of each sample are calculated by taking volume (V) and mean mass (Mm).

4.2. Measurement Of Total Fractional Porosity (γ)

Thetotal fractional porosity (γ) present in the sintered component may be evaluated from thefollowing relation[7]:

$\gamma = 1 - (\gamma p / \gamma s)$ ------------------------ (1)

Where, γ = Fractional porosity of powder metallurgy component.
γp = Density of the sintered component.
γs = Density of the solid material.
Density of sintered component (γp) may be evaluated by the following relation:

$\gamma p = (Mp / Vp)$ -------------------------- (2)

Where, Mp = Mass of sintered component.
Vp = Volume of sintered component.
Density of solid material (γs) which is an alloy may be evaluated by the following relation:

$\gamma s = \gamma (\gamma i , xi)$ ----------------------------- (3)

Where, γi = Density of the individual alloying element.
xi = Mass fraction of the individual alloying element present in the alloy.

4.3 Measurement of Hardness Number

Hardness measurement for each sample of alloys is carried out in a Rockwell Hardness Testing Machine. For hardness measurement B-Scale was selected where major load applied was 100 Kgf and minor load applied was 10 Kgf and 1/16" Hardened Steel Ball is used as Indenter. Four indentations are made on the surface of each sample and the hardness values as obtained from the machine are recorded.

V. Determination Of Tribologzical Properties

The Tribological behaviour of cylindrical pins is investigated with the help of Pin-On-Disc test. The disc is made of hardened steel (EN-310) and driven by a motor through a reduction gearbox. This allows the disc to rotate a number of specified speeds within a speed range[8]. The disc has a diameter of 100 mm. and thickness of 8mm. the specimen is held on the rotating disc with the help of pin holder, in turn is attached to load cell which helps to determine the frictional force developed between the loaded specimen and rotating disc. Before conducting each test all the samples (pins) are polished by using (Grade: 120) emery paper. The surface of the disc is also cleaned with jute to remove any dirt or grease. The height lost due to wear in µm of each sample (pins) is recorded after each rotation (Test) as shown by the Machine.Wear measurement for each sample of five alloys is carried out in a Wear Friction Monitor. Wear of each sample (pin of 12mm. diameter) in terms of height loss in µm has been measured by varying the sliding speed 200 RPM, 400 RPM, 600 RPM and 800 RPM and the applied load has been varied 20N, 40N, 60N and 80N for each Sliding Speed respectively by keeping track diameter fixed at 70 mm.

5.1 Measurement of co-efficient of friction.

The frictional co-efficient may be measured by using Coulomb´s law. Dry friction or Coulomb´s friction refers to the tangential component of the contact force between two dry surfaces in relative movement. The co-efficient of friction:

$$\mu = Fr/F \qquad \ldots\ldots\ldots\ldots (4)$$

Where, Fr= Frictional Force and F= force applied.

5.2 Measurement of wear rate.

The Wear rate may be calculated by using the following relationship[9];

$$Wr = (M1-Mf)/\ [t \times (\pi DN/1000)\} \qquad \ldots\ldots\ldots\ldots\ldots\ldots (5)$$

Where, MI = initial mass (gm.).
Mf = final mass (gm.).
t = time of rotation in minute.
D = Track diameter (mm).
N = rpm.
Wr = gm. /meter of rotation
Sliding Speed = ΠDN/1000 m/min

VI. Results And Discussions

6.1 Effect of Composition on Density.

Mass and volume for each sample of five alloys are measured with the help of Digital Balance and Vernier Caliper respectively, which are being used to calculate the Density of the same. Acquired data are listed below in the following table:-

Table 4: Dimensions and volume of samples

Alloy Specimen		Diameter (d) in mm.	Mean Diameter(dm) in mm.	Length (l) in mm.	Mean Length(lm) in mm.	Volume (V) in mm^3.
Alloy p	Sample: P1	12.24	12.25	26.64	26.62	3136.18
		12.24		26.68		
		12.26		26.66		
	Sample: P2	12.26	12.27	10.48	10.52	1243.02
		12.28		10.56		
		12.26		10.52		
	Sample:Q1	12.34	12.36	18.00	18.04	2235.25

Alloy Q		12.38		18.04		
		12.38		18.08		
	Sample:Q2	12.40	12.39	10.38	10.42	1255.42
		12.38		10.46		
		12.38		10.42		
Alloy R	Sample:R1	12.40	12.42	20.90	20.96	2537.80
		12.44		21.02		
		12.42		20.96		
	Sample:R2	12.46	12.46	11.16	11.22	1367.31
		12.48		11.28		
		12.44		11.22		
Alloy S	Sample:S1	12.54	12.56	17.02	16.98	2102.29
		12.58		17.08		
		12.58		16.90		
	Sample:S2	12.48	12.50	12.00	12.12	1486.49
		12.50		12.24		
		12.52		12.12		
Alloy T	Sample:T1	12.74	12.76	22.26	22.27	2846.06
		12.78		22.28		
		12.76		22.28		
	Sample:T2	12.80	12.78	11.74	11.76	1507.70
		12.78		11.76		
		12.78		11.78		

Table 5: Mass, Volume and Mean Density of Samples

Alloy		Specimen Mass (M) in gm.	Mean Mass (Mm) in gm.	Volume (V) in mm3	Density (ρ) in gm./cm3	Mean Density(ρm) in gm./cm3
Alloy P	Sample:P1	7.546	7.547	3136.18	2.400	2.415
		7.548				
		7.548				
	Sample:P2	3.021	3.020	1243.02	2.430	
		3.019				
		3.020				
Alloy Q	Sample:Q1	5.220	5.220	2235.25	2.330	2.350
		5.219				
		5.220				
	Sample:Q2	2.973	2.975	1255.42	2.370	
		2.975				
		2.975				
Alloy R	Sample:R1	5.877	5.879	2537.80	2.316	2.314
		5.881				
		5.879				
	Sample:R2	3.159	3.161	1367.31	2.312	
		3.159				
		3.163				
Alloy S	Sample:S1	4.755	4.758	2102.29	2.263	2.266
		4.758				
		4.761				
	Sample:S2	3.370	3.371	1486.49	2.268	
		3.372				
		3.371				
Alloy T	Sample:T1	6.190	6.188	2846.06	2.174	2.178
		6.191				
		6.186				
	Sample:T2	3.285	3.288	1507.70	2.181	
		3.291				
		3.288				

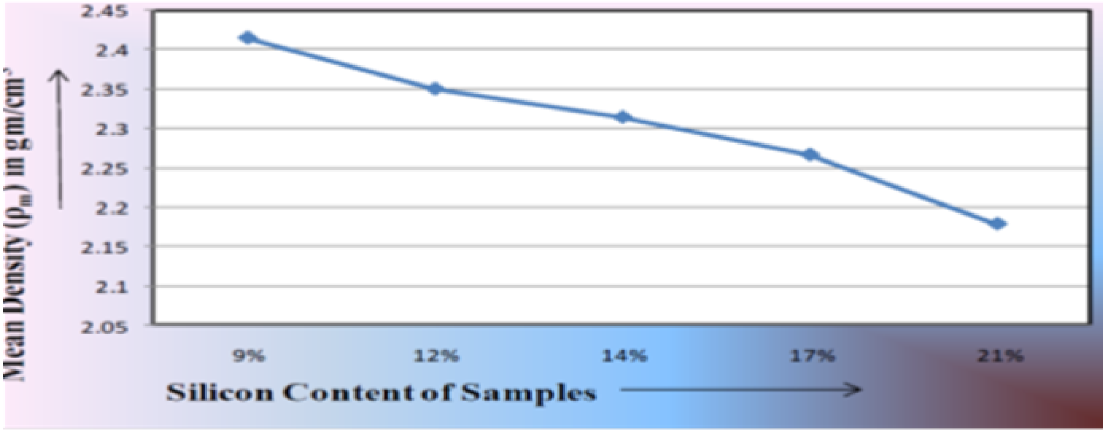

Figure 1 Density of Samples at different Silicon Content

The Densities for alloys Al-9%, Al-12%, Al-14%, Al-17% and Al-21% are found to be 2.415 gms/cm3, 2.350 gms/cm3, 2.314 gms/cm3, 2.266 gms/cm3 and 2.178 gms/cm3 respectively.

It is observed from the above data that the density of samples is decreasing with the increase in Silicon content. It is due tSilicon content The density of alloy decreases with increase in silicon content as it has lower density(i.e. 2.34 gms/cm3) than that of Aluminium (i.e. 2.67 gms/cm3).

6.2 Effect of Composition on Porosity

Table 6: Fractional porosity of samples

Total Fractional Porosity (γ)	Alloy P (Al-9%Si)	Alloy Q (Al-12%Si)	Alloy R (Al-14%Si)	Alloy S (Al-17%Si)	Alloy T (Al-21%Si)
	0.16	0.18	0.19	0.20	0.23

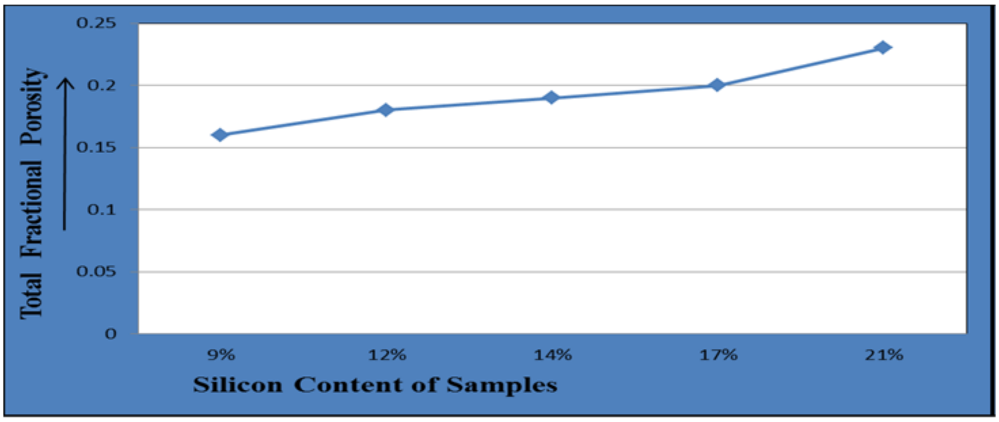

Figure 2: Fractional Porosity of Samples at different Silicon Content

It is observed from the above data that the porosity of the samples is increasing with the increase of Silicon amount. It may be due to the decrease in density of the alloy samples with increasing Silicon amount. So, it can be concluded that the Porosity of the alloy is inversely proportional to the Density of the alloy samples.

6.3 Effect of Composition on Hardness

Table 7: Hardness of alloy samples

Alloy Specimen		Hardness (HRB)	Average Hardness (HRB)	Average Hardness (HRB)
Alloy P	Surface:1	66	66.00	65.50
		65		
		66		
		67		
	Surface:2	64	65.00	
		66		
		65		

		65		
Alloy Q	Surface:1	68		
		69		
		68		
		70	68.75	
	Surface:2	70	69.25	69.00
		70		
		69		
		68		
Alloy R	Surface:1	72	72.00	72.13
		73		
		72		
		71		
	Surface:2	73	72.25	
		73		
		72		
		71		
Alloy S	Surface:1	75	76.00	76.50
		77		
		76		
		76		
	Surface:2	77	77.00	
		78		
		77		
		76		
Alloy T	Surface:1	82	82.25	82.13
		81		
		84		
		82		
	Surface:2	81	82.00	
		81		
		83		
		84		

The Brinell hardness numbers (HRB) for alloys Al-9%Si, Al-12%Si,Al-14%Si,Al-17%Si and Al-21%Si are found to be 65.50, 69.00,72.13,76.50 and 82.13 respectively. This shows that hardness of the Al-Si alloy increases with the increase in the weight percentage of silicon. This is due to the increment of silicon amount which is harder than Aluminium.

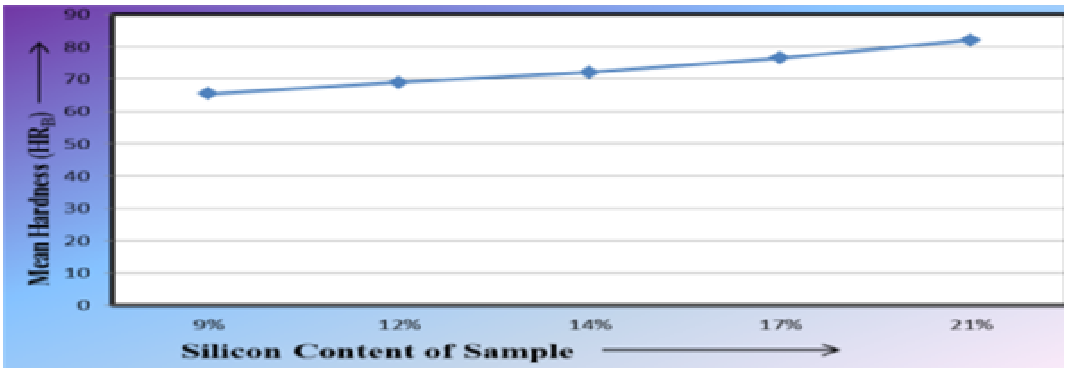

Figure 3 Mean Hardness of alloy with varying composition of silicon

6.4 Effect of Composition on Wearing Property

Wear measurement for each sample of five alloys is carried out in a Wear Friction Monitoring Machine. Wear of Specimen is measured by varying the Sliding Speed(200RPM, 400RPM, 600RPM and 800RPM)and the applied load (20N, 40N, 60N, 80N for each Sliding Speed respectively).The Wears as shown by the wear and friction monitoring machine are listed below.

Table 8: Wear of Al-Si alloy specimen at applied load 20N

Load in (N)	Speed in (RPM)	Alloy-P Wear in (µm)	Alloy-Q Wear in (µm)	Alloy-R Wear in (µm)	Alloy-S Wear in (µm)	Alloy-T Wear in (µm)
20	200	61	40	27	20	11
20	400	93	61	40	28	17
20	600	133	96	66	45	32
20	800	182	130	95	64	50

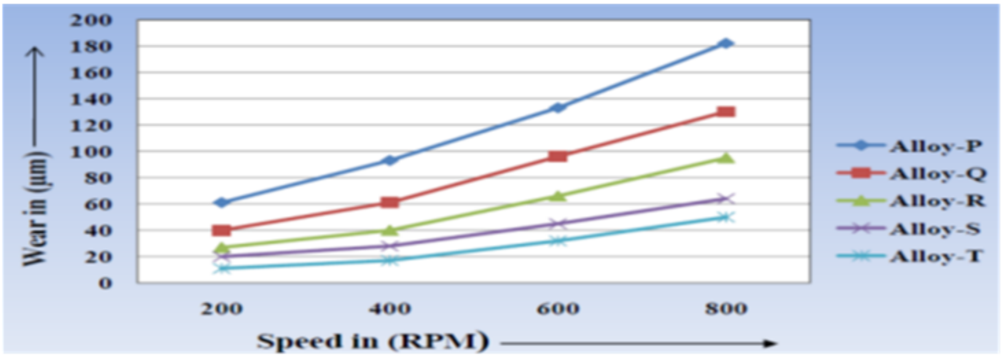

Figure 4: Wear Vs Sliding Speed of Al-Si Alloy Specimen at 20N applied Load

Table 9: Wear of Al-Si alloy specimen at applied load 40N

Load in (N)	Speed in (RPM)	Alloy-P Wear in (µm)	Alloy-Q Wear in (µm)	Alloy-R Wear in (µm)	Alloy-S Wear in (µm)	Alloy-T Wear in (µm)
80	200	195	176	165	156	147
80	400	231	198	179	164	155
80	600	271	228	205	181	173
80	800	320	272	235	201	191

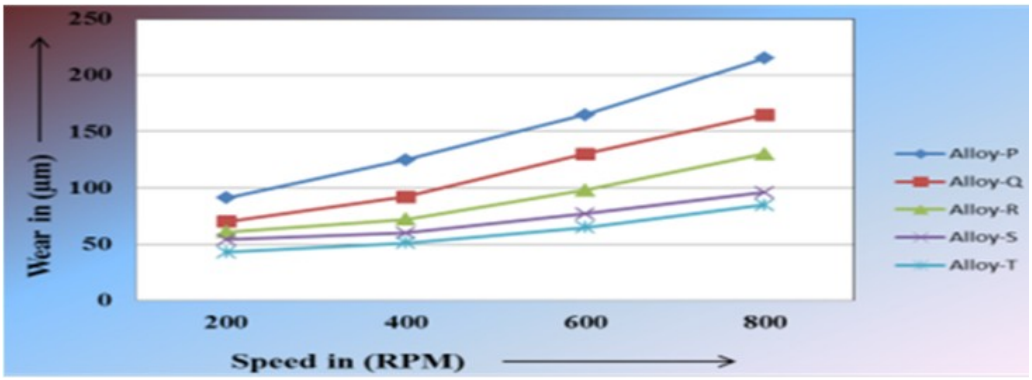

Figure 5: Wear Vs. Sliding Speed of Al-Si Alloy Specimen at 40N applied Load

Table 10: Wear of Al-Si alloy specimen at applied load 60N

Load in (N)	Speed in (RPM)	Alloy-P Wear in (µm)	Alloy-Q Wear in (µm)	Alloy-R Wear in (µm)	Alloy-S Wear in (µm)	Alloy-T Wear in (µm)
60	200	133	112	103	95	85
60	400	169	135	115	102	93
60	600	209	170	142	119	109
60	800	257	210	173	138	128

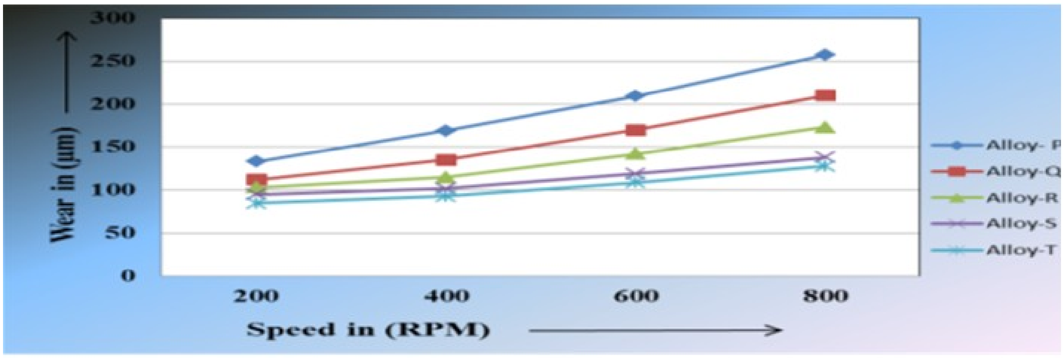

Figure 6: Wear Vs Sliding Speed of Al-Si Alloy Specimen at 60N applied Load

Table 11: Wear of Al-Si alloy specimen at applied load 80N

Load in (N)	Speed in (RPM)	Alloy-P Wear in (μm)	Alloy-Q Wear in (μm)	Alloy-R Wear in (μm)	Alloy-S Wear in (μm)	Alloy-T Wear in (μm)
80	200	195	176	165	156	147
80	400	231	198	179	164	155
80	600	271	228	205	181	173
80	800	320	272	235	201	191

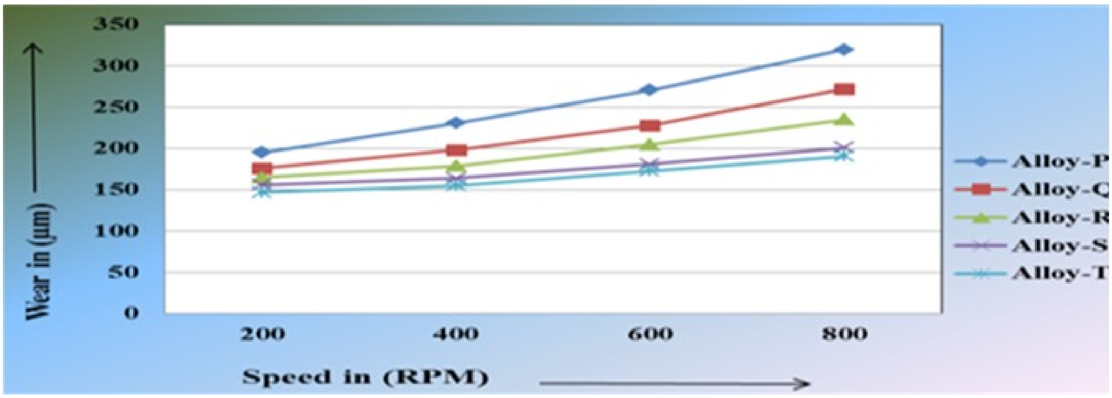

Figure 7: Wear Vs Sliding Speed of Al-Si Alloy Specimen at 80N applied Load

It is noticed that the height loss due to wear decreases with the increase in the percentage of silicon. The decrease in height loss with increasing percentage of silicon can be attributed to the presence of hard silicon particles adhered to the alloy. It is also noticed that due to the variation of the applied load the wear behavior is affected. The wear increases with the increase of applied load. This happens due to more frictional forces generated by more applied loads.

6.5 Composition Analysis

The following wt% of Al & Si are taken from the report given by the Eastern Testing Laboratory.

Table 12: Weight percentage of Al and Si Present in Al-Si p/m alloys

Alloy Specimen	Silicon (%)	Aluminium (%)
Alloy P	9.03	85.86
Alloy Q	12.02	82.87
Alloy R	13.95	81.06
Alloy S	16.95	78.13
Alloy T	20.91	74.15

The weight percentage of Silicon in Alloy-P (Al-9%Si)and Alloy-Q (Al-12%Si)is found to be 9.03% and 12.02% which is very close to 9% and 12% respectively. This suggests that sintered structure obtained is very sound. It can be seen that there is no loss of silicon and Aluminium in evaporation. The weight percentage of Silicon in Alloy-R (Al-14%Si), Alloy-S (Al-17%Si) and Alloy-T (Al-21% Si) is found to be 13.95, 16.95 and 20.91 which are still close to 14%, 17% and 21% respectively. This may happen due to some loss of Silicon in evaporation or this may be minor manual fault.

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