Effect of Silicon on Microstructure and Mechanical Properties of Al-Si Piston Alloys

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Abstract — *Al-Si alloys are in demand for several structural devices of their high strength to weight ratio. The enhancement in properties is further observed when suitably alloyed with the different elements. Al-Si alloy find their application mostly in automobile engineering. Si in the matrix nucleates as needle structure when solidified. These needle structures when modified exhibit very mechanical and wear properties. The microstructure can be modified and mechanical properties can be improved by alloying and heat treatment. The typical alloying elements are copper, magnesium and nickel. The aim of this work was to determine the effect of Si content on the microstructure and mechanical properties of hypo eutectic, eutectic and hypereutectic Al–Si piston alloys .The alloys of different content of Si namely 4, 6, 8, 10, 14 and 16 % are produced by gravity die casting route in an electric resistance furnace. The paper also emphasises the role of heat treatment on the microstructure and hence the mechanical properties of the Al-Si piston alloy. The micro structural observations and mechanical properties namely tensile strength and hardness were investigated according to standard procedure. Ultimate tensile strength has increased with increase in silicon content. The hardness of the samples increases with the increase in silicon content. The application of heat treatment produced a finer microstructure and resulted in a uniform distribution of the intermetallic compounds and it modifies the eutectic Si phase and hence improves the mechanical properties of the alloy.*

Keywords — *Aluminium alloys, alloying elements, heat treatment, microstructure, tensile strength, material removal rate,*

I. INTRODUCTION

Aluminum is one of the most abundant metals available in the earth's crust as bauxite with wide range of applications in the modem world. There are many reasons for aluminum's continued expansion into newer and wider fields of application. Light weight, excellent specific strength, high thermal and electrical conductivities, high reflectivity, good corrosion resistance, excellent workability, and attractive appearance are some of aluminum's most appealing properties. However, its relatively low strength and poor cast ability limit its use largely to the production of rotor castings for electrical motors and other applications in which high electrical conductivity is required.

The costs involved in producing aluminum are high compared to steel production, as the energy requirements to reduce the metal from the oxide is much higher. However, due to the higher specific strength of aluminum alloys, a comparative higher corrosion resistance due to the formation of a stable oxide layer and ease of working results in aluminum alloys being competitive with ferrous alloys in engineering applications .

The Aluminum Association’s Designations and Chemical Composition Limits for Aluminum Alloys in the Form of Castings and Ingot lists for each alloy 10 specific alloying elements and also have a column for “others”. Not all of the listed elements are major alloying ingredients in terms of an alloys intended uses; and some major elements in one alloy are not major elements in another. Also, some elements, like Sr for example, can be very important to microstructure control and mechanical properties but are not specifically identified in the Aluminum Association document and are instead are merely included in the category “others”.

For the purposes of understanding their effects and importance, alloying elements for the majority of alloys are probably best classified as major, minor, microstructure modifiers or impurities; understanding, however, that impurity elements in some alloys might be major elements in others.

- **Major elements** typically include silicon (Si), copper (Cu) and magnesium (Mg).
- **Minor elements** include nickel (Ni) and tin (Sn) -- found largely in alloys that likely would not be used in high integrity die castings.
- **Microstructure modifying elements** include titanium (Ti), boron (B), strontium (Sr), phosphorus (P), beryllium (Be), manganese (Mn) and chromium (Cr).
- **Impurity elements** would typically include iron (Fe), chromium (Cr) and zinc (Zn).

In this study, a comparative study due to the effect of grain refinement and modification on the microstructure and mechanical properties of cast and heat treated alloy has been carried out. The application of heat treatment increases the yield strength and an overall improvement in the mechanical properties of the grain refined/modified alloy.

II. LITERATURE REVIEW

The Tsushima-Naka [2] says Aluminum casting alloys with silicon as the major alloying elements are the most important commercial casting alloys because of their superior casting characteristics. This study aimed to investigate solidification and mechanical behavior of Al- Si alloy against both the molding conditions and silicon content (3%- 15% Si). However, an increase of both the ultimate tensile strength and the hardness is obtained by the increase of the silicon content. With the increase of silicon content the wear rate decrease and coefficient of friction increase.

Dheerendra Kumar Dwivedi [3] says that the influence of sliding interface temperature on friction and wear behavior of cast Al–(4–20%) Si–0.3% Mg has been reported. Wear and friction tests were performed under dry sliding conditions using pin on disc type of friction and wear monitor with the data acquisition system conforming to ASTM G99 standard. It was found that sliding interface temperature has close relation with wear and friction response of these alloys. Initial rise in interface temperature reduces the wear rate and as soon as a critical temperature (CT) is crossed, wear rate abruptly increases in case of all the compositions used in this investigation. Friction coefficient during the sliding of all aluminum alloys (irrespective of silicon content) first decreases with the rise in interface temperature and then abruptly increases beyond certain critical temperature. Critical temperature was found to be a function of alloy composition, i.e. silicon content. Hypoeutectic alloys showed lower critical temperature than the hypereutectic alloys

Milind G Kalhapure [4] says that Mechanical testing plays an important role in evaluating fundamental properties of engineering materials as well as in developing new materials and in controlling the quality of materials for use in design and construction. If a material is to be used as part of an engineering structure that will be subjected to a load, it is important to know that the material is strong enough and rigid enough to withstand the loads that it will experience in service. As a result engineers have developed a number of experimental techniques for mechanical testing of engineering materials subjected to tension, compression, bending or torsion loading. The influence of silicon on mechanical properties such as ductility, hardness, toughness, yields strength of Aluminum alloy. The silicon content is varied from 5, 7, 9, 12.5 and 14% in five different aluminum alloys. The mechanical properties were measured using the tension test. It was found that the ductility has been increased after increase in silicon percentage. Also there is a significant change in ultimate tensile strength and hardness due to silicon.

Hesham Elzanaty [5] The aim of this work was to determine the effect of Si content on the mechanical properties of near eutectic and hypereutectic Al–Si alloys with high Si content. The alloys of different content of Si–namely, 2, 4, 6, 8, 11.6, 12.5, 15, 17 and 20 wt.% are produced by stir casting route in an induction heating furnace. The mechanical properties namely Tensile strength and Hardness were investigated according to standard procedure. Tensile tests were carried out with universal testing machine. Yield strength and ultimate tensile strength has increased with increase in silicon content. But, percent elongation decreases with the increase of silicon content

M. Gupta [6] says that three aluminum–silicon alloys containing 7, 10 and 19 wt % silicon were synthesized using a novel technique commonly known as disintegrated melt deposition technique. The results following processing revealed that a yield of at least 80% can be achieved after defacing the shrinkage cavity from the as-processed ingots. Microstructural characterization studies conducted on the as-processed samples revealed an increase in the volume fraction of porosity with an increase in silicon content. Porosity levels of 1.07, 1.51 and 2.65% attained in the case of Al–7Si, Al–10Si, and Al–19Si alloys indicates the near-net shape forming capability of the disintegrated melt deposition technique. The results of aging studies conducted on the aluminum–silicon alloys revealed similar aging kinetics irrespective of different silicon content. Results of ambient temperature mechanical tests demonstrate an increase in matrix microhardness and 0.2% yield stress and decrease in ductility with an increase in silicon content in aluminum.

Rajneesh Kumar Verma[7] says that 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 luster 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, Cu 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.

Effects of Alloying Elements [1] play an important role in manufacturing of engine parts. According to the requirement they classified as major elements and minor elements. Among these silicon plays an important role in manufacturing of engine parts.

III. METHODOLOGY AND EXPERIMENTS

The methodology adopted in carrying out the work includes following steps:

1. Processing of Aluminum alloys according to the increasing order of silicon contents (4% - 16%)
2. Manufacturing of aluminum alloys by gravity die casting
3. Sample preparation for microstructure & mechanical testing according to specification
4. Analysis of microstructure and various mechanical properties before heat treatment
5. Heat treatment done according to T6 condition
6. Analysis of microstructure and various mechanical properties after heat treatment
7. Comparison of results before and after heat treatments

Figure 3.1 Methodology of experiment

The aluminum alloy, which is used in the present study, was melted in the 18kW electrical resistance melting furnace. Aluminium Alloy was taken cleaned thoroughly with acetone to remove the adherent dust/oily material, preheated and charged to the clay bound graphite crucible already placed in the furnace at a temperature of around 500°C and melted in the furnace at 750°C under coverall flux. The ingots are preheated before charging for melting. Degassing is done to avoid the hydrogen entrapment. Degassing is done by passing N_2 gas to the molten metal through the sulphuric acid. Sulphuric acid will act as purifier and the N_2 gas will remove the H_2 from the molten metal. The furnace and ovens are periodically checked for rate of heating and set temperature. When the crucibles kept in the furnace attains 700-730°C, the preheated ingots were charged into the crucible. Half of the coverall flux (preheated to 120-130°C) is sprinkled over the charge during the time of charging itself. The remaining half of the flux was sprinkled when the charge was just melting. The temperature of the melt was measured and monitored using Chromel-Alumel thermocouple. After the degassing of 45 - 60 minutes the crucible is taken out of the furnace and the slag is removed. The molten metal is then poured into permanent mould in the case of gravity casting.

Heat-treatment is of major importance since it is commonly used to alter the mechanical properties of cast aluminum alloys. Heat-treatment improves the strength of aluminum alloys through a process known as precipitation-hardening which occurs during the heating and cooling of an aluminum alloy and in which precipitates are formed in the aluminum matrix. The improvement in the mechanical properties of Al alloys as a result of heat treatment depends upon the change in solubility of the alloying constituents with temperature.

The tension test is one of the most commonly used tests for evaluating mechanical properties of the materials. The tests were conducted on the specimens after the precipitation hardening heat treatment process. The specimens were prepared as per the standard size. In this test a tensile force is applied by the machine, resulting in gradual elongation and eventual fracture of the test specimen. The hardness tests of all the samples have been done using a Vickers hardness testing machine. For each composition, six indentations were taken and average value.

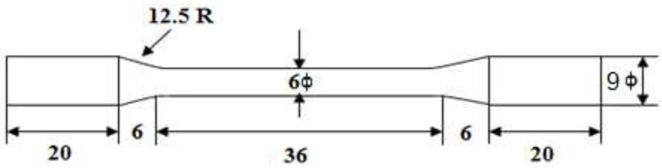

Figure 3.2 Tensile test specimens

Wear rate of aluminium-silicon casting alloys was studied by using a pin-on-disc wear tester. The typical pin specimen is cylindrical or spherical in shape. Wear test carried out in pin-on-disk with three conditions. Generally three conditions of piston alloy are:

1. Sliding distance – 1200m
2. Load – 20N
3. Velocity- 2m/s

IV. RESULTS AND DISCUSSIONS

Experiments were performed on permanent mould castings with silicon varying from 4 to 16 % by weight. The chemical compositions of the alloys were measured by SPECTRO-MAX Optical Emission Spectrometer using arc spark excitations which are listed in Table 4.1.

Table 4.1 Chemical composition of the alloys

Alloy	Si	Cu	Mg	Ni	Fe	Mn	Ti	Al
Alloy 1	4	3.000	1.000	1.78	0.926	0.030	0.010	REST
Alloy 2	6	3.000	1.000	1.78	0.272	0.016	0.000	REST
Alloy 3	8	3.000	1.000	1.78	0.373	0.041	0.017	REST
Alloy 4	10	3.000	1.000	1.78	0.432	0.070	0.020	REST
Alloy 5	14	3.000	1.000	1.78	0.414	0.045	0.015	REST
Alloy 6	16	3.000	1.000	1.78	0.528	0.046	0.026	REST

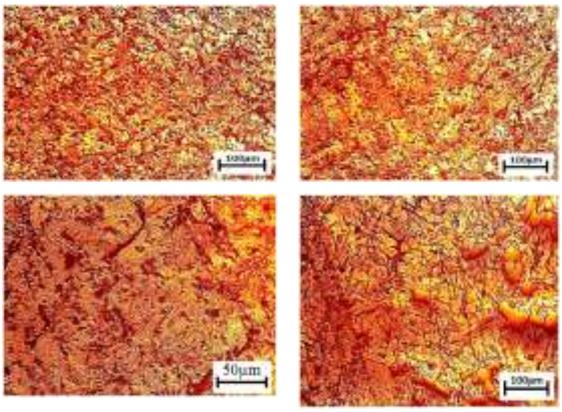

Figure 4.1 Microstructure images before heat treatment

The photo-micrograph in figure 4.1 shows inter-dendritic Al-Si eutectic in primary alpha solid solution of aluminium and also eutectic particles of Cu-Al has not dissolved being cast and cooled slowly. The eutectic particles of Cu-Al_2 are also present as dark script in grain boundaries.As the silicon content increases from 4%-10% very low content of primary silicon particles was observed. Large and medium sized formation of primary silicon particles observed at 14% silicon also complete un-dissolved Cu-Al_2 with some free copper in aluminium solid solution was observed. Increases in silicon content from 14 to 16% increases the volume fraction of primary silicon crystals rest of the features are not significantly affected.

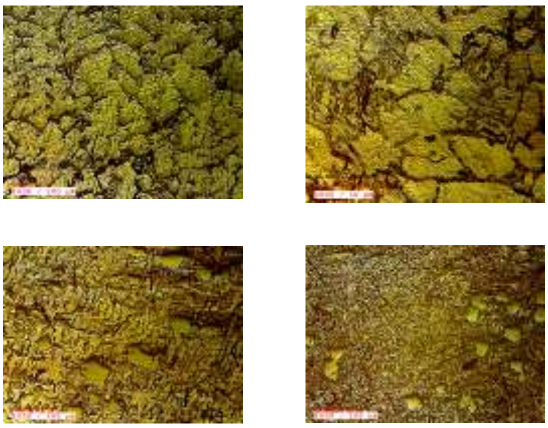

Figure 4.2 Microstructure images after heat treatment

Optical microphotographs of cast Al–(4–20) % Si alloys are shown in Figure 4.2 It is observed that the primary -aluminium grains are predominantly present in structure of cast Al–4% Si. Little amount of eutectic silicon can also be seen in the inter-dendritic region. Optical microphotograph of cast Al–8% Si alloy shows that primary-aluminium grains are embedding in the eutectic. Eutectic silicon can be seen in the inter-dendritic region. It is observed that the addition of silicon has increased the eutectic amount present in the inter-dendritic region. Al–12% Si alloy also shows that primary aluminium grains are present in the inter-dendritic region. Moreover, addition of silicon increases the amount of eutectic present along the grain boundaries. Optical microphotograph of cast Al–16% Si alloy shows coarse polyhedral shaped primary silicon crystals in matrix of eutectic. Increase in silicon content from 14 to 16% increases the volume fraction of primary silicon crystals rest of the features is not significantly affected. It is expected that increase in the proportion of eutectic and primary silicon crystals with the addition of silicon would increase the hardness and affect the wear behaviour.

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. Tensile test is the most common procedure; hence it is an easy way to get information about the materials strength and deformation properties in single tests. Some of the results from the tensile test are ultimate tensile strength, yield strength and percent elongation. it may be observed that as the silicon content in the alloy increases, the strength properties (ultimate tensile strength and tensile stress) of Al–Si alloys also increase to maximum value 150MPa at 14 wt% of silicon. However, the percent elongation decreases continuously with increasing silicon. Hardness of the Al–Si alloy increases with the increase in the silicon content. This may be due to the increment of silicon amount, which is harder. However, when the primary silicon appears as coarse polyhedral particles with increasing silicon content, the hardness goes on increasing because of the increase in the number of silicon particles.

The tensile properties of the as cast and heat treated samples made with different Si content are examined. It can be seen that the tensile strengths are different, with the varying Si content.

Table 4.2 Effect of material removal rate before and after heat treatment

Effect of material removal rate before heat treatment

Sample Id	Initial weight	Final weight	Removal Rate
Alloy 1	6.637	6.630	0.007
Alloy 2	6.013	6.003	0.01
Alloy 3	6.171	6.165	0.006
Alloy 4	5.815	5.805	0.01
Alloy 5	6.161	6.153	0.008
Alloy 6	6.661	6.657	0.004

Effect of material removal rate before heat treatment

Sample Id	Initial weight	Final weight	Removal Rate
Alloy 1	6.423	6.412	0.002
Alloy 2	6.197	6.194	0.003
Alloy 3	5.877	5.871	0.006
Alloy 4	5.801	5.795	0.006
Alloy 5	6.120	6.113	0.007
Alloy 6	6.646	6.635	0.011

Hardness of the Al–Si alloy increases with the increase in the silicon content. This may be due to the increment of silicon amount, which is harder. However, when the primary silicon appears as coarse polyhedral particles with increasing silicon content, the hardness goes on increasing because of the increase in the number of silicon particles

It was observed that material removal rate of alloys without heat treatment much higher than material removal rate of alloys with heat treatment. So for piston alloy having heat treated with T6 conditions have shown less material removal as shown in table 4.2

V. CONCLUSIONS

- The present work deals with the study of the variation of silicon content in the aluminium-silicon-copper-magnesium alloy.
- Effect of addition of alloying elements has studied.
- Literatures related with the topic were collected. From the collected literatures, it was understood that piston is one of the important part in an automobile and is always subjected severe load conditions for prolonged loading cycles.
- Case studies related with piston failures clearly indicate that the composition of the materials play an important role in the tensile strength, hardness, wear and microstructure.
- The present composition of the piston materials plays an important role in defining the thermo-mechanical properties of the component.
- Microstructure and various mechanical properties have tested.

From the present study can concluded that, with the increase of silicon content of the aluminum-silicon casting alloys the cooling rate decreased as also a decrease of the liquidus temperature was observed up to 10% and then increased with increasing Si%. Where with the increase of silicon content the ultimate tensile strength and hardness increased, and high coefficient of friction and high wear resistance was produced. The change of mold thickness affected on the cooling rate of aluminum-silicon casting alloys so on the microstructure. A pronounced change in the mechanical and tribological properties also obtained.

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