

“Strength and fracture studies of as-cast Al-Si-Cu alloys”

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June 2008

Dedicated to my Loving Parents

CERTIFICATE

This is to certify that the thesis entitled "Strength and fracture studies of as-cast Al-Si-Cu alloys" submitted by Mr. Abhishek Sharma Roll No. 60602001 in partial fulfillment of the requirement for the award of the degree of MASTERS OF TECHNOLOGY in Materials Science and Engineering, Thapar University Patiala, is a record of candidates own work, carried out by him under our supervision and guidance. The matter embodied in this report is of the candidate's own record and not submitted to any other university in any part or full form for the award of such kind of a degree.



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ABSTRACT

Aluminum-silicon (Al-Si) alloys are an important class of materials, which has great interested in aerospace and automobile industries, due to their superior properties like high strength to weight ratio, corrosion resistance and excellent castability. Within this family of alloys, Al-Si-Cu cast alloy (3XXX series) is frequently employed in automotive applications. In the present work, the strength and fracture studies of as-cast Al-Si-Cu alloys have been studied. As cast alloys have been characterized using XRD and optical microscope. To evaluate the strength of these alloys, a Tensometer has been employed and the fracture surfaces have been observed under SEM to understand the mode of fracture. It has been observed that the fracture surface of the alloys mainly shows brittle characteristics. The porosity and blowhole present in the cast alloy has been the dominating factor for low strength of the alloys.

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LIST OF ABBREVIATIONS

SEM	Scanning Electron Microscope
X-RD	X-Ray Diffraction Technique
CTE	Coefficient of linear Thermal Expansion
UTS	Ultimate Tensile Strength
YS	Yield Strength

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Aluminum cast alloys are the most versatile of all foundry alloys and generally have high castability ratings. Among them, Al-Si alloys are by far the most important commercial cast alloys (constituting 85% to 9.0% of the total aluminum cast parts produced), on account of their superiority to other alloy systems in casting characteristics. In the present work, Al-Si-Cu cast alloy, belonging to the Al-Si alloy system and represented respectively by 3XXX alloy, was selected for study, due to the high demand of these alloys in the automobile industry, which is the largest consumer of Al-Si cast alloys.

Tensile property is one of the important mechanical properties that is routinely determined and used in design calculations. Tensile testing is one of the most common methods used to measure the static mechanical properties of a metallic material. From a complete record of tensile testing data, a lot of important information can be obtained, such as the properties and degrees of elastic and plastic deformations, yield strength, ultimate tensile strength, the energy needed for tensile fracture. The engineering tension test is widely used to provide basic design information on the strength of materials and as an acceptance test for the specification of materials. In the tension test, a specimen is subjected to a continually increasing uniaxial tensile force while simultaneous observations are made of the elongation of the specimen. [DIE 1976]. Several literatures are available, which shows an increase in strength of aluminum after alloy addition like silicon and copper [SAM 2008]. However, due to alloy addition some properties (corrosion) are adversely affected.

Porosity in castings is always detrimental to mechanical properties, especially ductility, fracture toughness, fatigue life and in some cases, the surface finish. It also reduces the casting size, depreciates corrosion stability and has a particularly bad influence on dynamic strength. Two types of porosity are observed in Al-Si cast alloys: (a) gas porosity, mainly caused by the evolution of dissolved hydrogen due to the difference in its solubility in solid and liquid aluminum, or reactions in the liquid, and (b) shrinkage

porosity created by the density difference between liquid and solid metals and inadequate liquid mobility (limited feeding) [FAN 1989].

In the present work, aluminum-silicon-copper alloys with three different compositions have been synthesized by casting route. The tensile samples have been prepared from the as-cast alloy by machining. A Tensometer has been employed to evaluate the tensile strength of the alloys and the fracture surfaces have been observed under SEM to evaluate the mode and nature of fracture.

Aluminum alloys containing silicon as the major alloying element offer excellent castability, high wear and corrosion resistance, good weldability, low specific gravity, high thermal conductivity, reduction of the coefficient of thermal expansion (due to the added silicon), and good retention of physical and mechanical properties at elevated temperatures. It is for this reason that aluminum-silicon (Al-Si) alloy castings constitute 85 to 90% of the total aluminum cast parts produced. Due to their excellent strength-to-weight ratio, Al-Si castings obtain extensive applications in the automobile industry. [MAD 1996]

Aluminum casting alloys are commonly grouped into various alloy series, depending upon the alloying elements they contain. Among the most common aluminum casting alloys are 319.0 (Al-6Si-3.5Cu), 332.0 (Al-9.5Si-3Cu-1.0Mg), 355.0 (Al-5Si-1.3Cu-0.5Mg), A356.0 (Al-7Si-0.3Mg), A357.0 (Al-7Si-0.5Mg), 380.0 (Al-8.5Si-3.5Cu), 383.0 (Al-10.5Si-2.5Cu), 384.0 (Al-11.2Si-3.8Cu), 390.0 (Al-17.0Si-4.5Cu-0.6Mg), 413.0 (Al-12Si) and 443.0 (Al-5.2Si).

2.1 DESIGNATION SYSTEM OF ALUMINUM CASTING ALLOY SERIES

The most commonly used designation system for aluminum casting alloys is the three digit system (i.e., 1xx.x, 2xx.x, etc.) proposed by the Aluminum Association (AA). The first digit indicates the alloying group. The second and the third digits identify the specific aluminum alloy according to its alloying elements, or indicate aluminum purity for the aluminum (1xx.x) series. A decimal value always follows, where decimal .0 in all cases represents chemical composition limits for casting, while decimals .1 and .2 concern chemical composition limits for ingots. Several AA alloy designations also include a prefix letter, which distinguishes alloys of a general composition (with the same alloy number) only in percentage of impurities or minor alloying elements, e.g., 319, A319 and B319.

The AA designations of aluminum casting alloy series are given as follows.

1xx.x Series: Controlled unalloyed compositions (pure aluminum).

2xx.x Series: Aluminum alloys containing copper as the major alloying element.

Other alloying elements may be specified.

3xx.x Series: Aluminum-silicon alloys containing magnesium and/or copper.

4xx.x Series: Binary aluminum-silicon alloys.

5xx.x Series: Aluminum alloys containing magnesium as the major alloying element.

6xx.x Series: Unused.

7xx.x Series: Aluminum alloys containing zinc as the major alloying element.

8xx.x Series: Aluminum alloys containing tin as the major alloying element.

9xx.x Series: Unused.

2.2 Master alloy

The use of a master alloy offers distinct advantages:

- shorter dissolution times
- alloying at lower temperatures
- higher accuracy to meet specified composition limits
- improved metal yield

2.2.1 Al-Si master alloy

The Al-Si 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 1.65 at.% at the eutectic temperature.

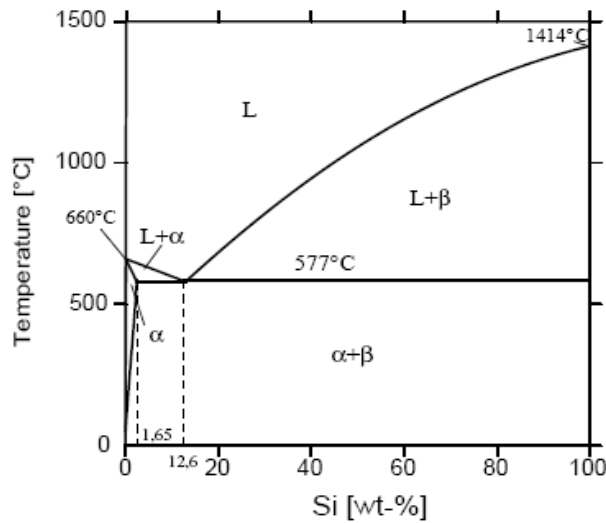


Fig2.1:- Al-Si phase diagram

Silicon is an important alloying element in most medium strength and some high strength wrought Aluminum alloys. The presence of Silicon in Aluminum alloys:

- imparts heat treatable properties in balanced combination with Magnesium.
- enhances the fluidity of casting alloys.
- lowers the melting point for brazing alloys.

2.2.2 Al-Cu Master alloy

Another alloy system of great commercial importance is aluminum-copper. This family of alloys (designated the 2xxx series) has nominal copper contents ranging from 2.3 to 6.3 wt%, making them hypoeutectic alloys as shown in figure:

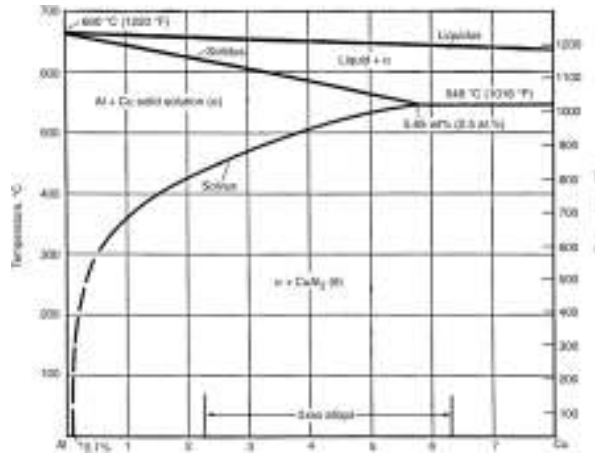


Fig2.2 Al-Cu Phase diagram

The solid-solution (α) region (below 0.1 wt% Cu), where the alloying atoms remain dissolved by substituting aluminum atoms in the aluminum/face-centered cubic (fcc) lattice. In this alloying region, the terminal (room-temperature) solid-state condition is essentially a monophasic structure (Fig.2.2).

-The solid-state region below the solvus line, where dispersed particles of the θ (Al_2Cu) intermetallic precipitate in a supersaturated aluminum-copper solid.

- The region to the right of the maximum solid-solubility point (5.65 wt% Cu), where the $\theta(\text{CuAl}_2)$ phase precipitates during solidification and thus forms a network of second-phase particles around the previously solidified α grains in the $L + \alpha$ region.

2.3 Al-Si-Cu alloys

Al-Si alloys are the most important alloys in automotive and aerospace industry. These alloys are the members of 3xxx family. The production of cast Al-Si alloys with improved quality (better structure and mechanical properties) involves:

- (1) Addition of alloying elements during the melting and treatment of liquid alloy (refining and/or modification)
- (2) Application of heat treatment, with the disadvantage of prolonged period of time and input energy
- (3) Stirring during solidification

(4) Plastic deformation (extrusion, rolling and forging)

The addition of grain refiners and modifiers converts large elongated α -Al dendrites into fine equiaxed α -Al dendrites and eutectic silicon (plate-like) into fine particles, respectively.

Strengthening of Al–Si alloys is achieved by adding small amount of Cu, Mg or Ni and the presence of silicon provides good casting properties. Copper improves impact toughness at the expense of ductility and corrosion resistance. Also copper results in the precipitation of CuAl_2 particles and depending of cooling rate and modifier level, this phase could appear as (Al–CuAl₂) fine eutectic colonies in the A very important finding is that alloys with the same chemical composition can have different microstructures and mechanical properties due to variations in the casting process, the use of a grain refiner, modifier, or both grain refiner and modifier and also by heat treatment. This means that different processing techniques can result in a range of mechanical properties, which affect the cutting process. Several experimental results have been reported describing the use of grain refiners and modifiers to obtain a fine-grained microstructure of eutectic Al–Si–Cu alloys. But Al–12Si–2.5Cu, Al–11Si–3.5Cu and Al–10Si–4.5Cu, cast alloys have not yet been sufficiently elucidated, except for hardness, and there are very few reports on tensile properties and fracture analysis.

2.4 Tensile property of material

The engineering tension test is widely used to provide basic design information on the strength of materials and as an acceptance test for the specification of materials. In the tension test, a specimen is subjected to a continually increasing uniaxial tensile force while simultaneous observations are made of the elongation of the specimen. [DIE 1976].

These mechanical properties determined from tension tests include, but are not limited to, the following:

- ✓ . Elastic deformation properties, such as the modulus of elasticity (Young's modulus) and Poisson's ratio
- ✓ . Yield strength and ultimate tensile strength
- ✓ . Ductility properties, such as elongation and reduction in area

✓ . Strain-hardening characteristics

In the tensile testing we make a graph between load v/s elongation after than convert into stress-strain curve. A typical engineering stress-strain curve is shown below.

The shape and the magnitude of the stress–strain curve of a material will depend on its composition, heat treatment, prior history of the plastic deformation, and the strain rate, temperature, and the state of the stress imposed during the testing .The parameters which are used to describe the stress-strain curve of a metal are the Tensile strength, yield strength or yield point, percent elongation, and reduction of area. The first two are strength parameter and last two indicate ductility.

In the conventional engineering tension test, an engineering stress-strain curve is constructed from the load-elongation measurements made on the test specimen (Fig.2.3). The engineering stress (s) used in this stress-strain curve is the average longitudinal stress in the tensile specimen. It is obtained by dividing the load (P) by the original area of the cross section of the specimen (A_0).

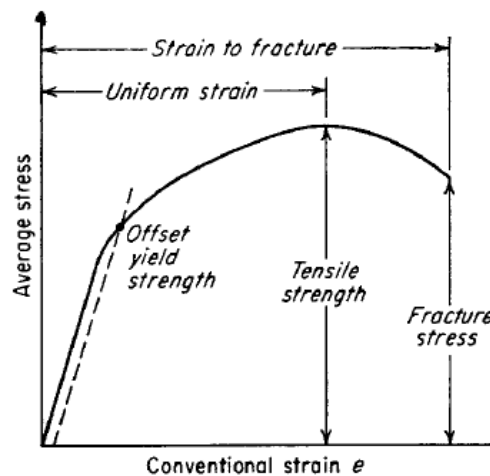


Fig-2.3 -Stress-Strain Curve

2.4.1 Measures of Yielding

The stress at which plastic deformation or yielding is observed to begin depends on the sensitivity of the strain measurements. With most materials, there is a gradual transition

from elastic to plastic behavior, and the point at which plastic deformation begins is difficult to define with precision. In tests of materials under uniaxial loading, three criteria for the initiation of yielding have been used: the elastic limit, the proportional limit, and the yield strength. Elastic limit, shown at point A in Fig. 2.4, is the greatest stress the material can withstand without any measurable permanent strain remaining after the complete release of load. With increasing sensitivity of strain measurement, the value of the elastic limit is decreased until it equals the true elastic limit determined from microstrain measurements. With the sensitivity of strain typically used in engineering studies (10^{-4} in./in.), the elastic limit is greater than the proportional limit. Determination of the elastic limit requires a tedious incremental loading-unloading test procedure. For this reason, it is often replaced by the proportional limit.

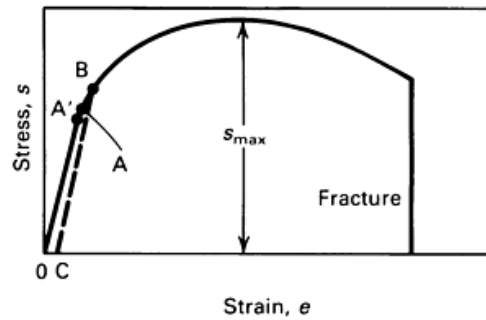


Fig2.4 Stress-Strain curve for yield point

Proportional limit, shown at point A' in Fig. 2.4, is the highest stress at which stress is directly proportional to strain. It is obtained by observing the deviation from the straight-line portion of the stress-strain curve. The yield strength, shown at point B in Fig. 2.4, is the stress required to produce a small-specified amount of plastic deformation. The usual definition of this property is the offset yield strength determined by the stress corresponding to the intersection of the stress-strain curve offset by a specified strain. The offset is usually specified as a strain of 0.2 or 0.1% ($e = 0.002$ or 0.001).

$$s_0 = \frac{P_{(\text{strain offset}=0.002)}}{A_0}$$

2.4.2 MEASURES OF DUCTILITY

Ductility is a qualitative, subjective property of material. In general, measurements of ductility are of interest in three ways.

1. To indicate the extent to which metal can be deformed without fracture in metalworking operations such as rolling and extrusion.

2. To indicate to the designer, in a general way, the ability of the metal to flow plastically before fracture. A high ductility indicates that the material is “forgiving” and likely to deform locally without fracture should the designer in the stress calculation or prediction of several loads.

3. To serve as an indicator of changes in impurity level or processing conditions. Ductility measurement may be specified to assess material “quality” even though no direct relationship exists between the ductility measurement and performance of service.

The conventional measures of ductility that are obtained from the tension test are the engineering strain at fracture e_f (usually called the elongation) and the reduction of area at fracture q . Both of these properties are obtained after fracture.

The yield strength is the stress required to produce a small specified amount of plastic deformation. The usual definition of this property is the small offset yield strength determined by the stress corresponding to the intersection of the stress-strain curve and a line parallel to the elastic part of the curve offset by a specified strain fig(2.4)

The slope of the initial linear portion of the stress-strain curve is the modulus of elasticity, or young’s modulus. The measurement of elasticity is a measure of the stiffness of the material. The greater the modulus, the smaller the elastic strain resulting from the application of a given stress.

The modulus of elasticity is determined by the binding forces between atoms. Since these forces cannot be changed without changing the basic nature of the material, it follows

that the modulus of elasticity is only slightly affected by alloying, heat treatment or cold-work.

2.4.3 Modulus of Elasticity

The slope of the initial linear portion of the stress-strain curve is the modulus of elasticity, or Young's modulus. The modulus of elasticity (E) is a measure of the stiffness of the material. The greater the modulus, the smaller the elastic strain resulting from the application of a given stress. Because the modulus of elasticity is needed for computing deflections of beams and other members, it is an important design value. The modulus of elasticity is determined by the binding forces between atoms. Because these forces cannot be changed without changing the basic nature of the material, the modulus of elasticity is one of the most structure-insensitive of the mechanical properties. Generally, it is only slightly affected by alloying additions, heat treatment, or cold work. However, increasing the temperature decreases the modulus of elasticity.

2.4.4 Ultimate Tensile Strength

The ultimate tensile strength (UTS) is the tensile strength of maximum engineering stress level in a tension test. The strength of a material is its ability to withstand external forces without breaking. In brittle materials, the UTS will be at the end of the linear-elastic portion of the stress-strain curve or close to the elastic limit. In ductile materials, the UTS will be well outside of the elastic portion into the plastic portion of the stress-strain curve. Since the UTS is based on the engineering stress, it is often not the same as the breaking strength. In ductile materials strain hardening occurs and the stress will continue to increase until fracture occurs, but the engineering stress-strain curve may show a decline in the stress level before fracture occurs. This is the result of engineering stress being based on the original cross-section area and not accounting for the necking that commonly occurs in the test specimen.

2.5 Porosity

In the metallurgical context, porosity refers to the presence of minute holes or cavities in a solid metal. Porosity is one of the defects normally present in Al-Si-Cu cast alloys. Extensive studies have been conducted, since the early 1950s, to understand the origins and characteristics of porosity formation. It is quite well understood that casting porosity is caused by the cooperative effects of shrinkage and dissolved gas; that is (a) shrinkage created by the density difference between the liquid and solid states of the metal, as well as inadequate liquid mobility (bad feeding), and (b) the evolution of dissolved gases (mainly hydrogen) due to the difference in the solubility's of these gases in the solid and liquid phases of the metal. In commercial practice, the formation of porosity is always considered to be a function of alloy composition, melt hydrogen level, and foundry processing parameters such as cooling rate, modification, alloying elements, grain refinement, inclusions, etc. With mechanical degassing facilities and some typical fluxes, it is possible to minimize the porosity content. Porosity in a casting always deteriorates its mechanical properties. It is particularly harmful to the ductility, fracture toughness, fatigue life and, in some cases, the surface finish of the casting.

2.5.1 Types of Porosity

2.5.1.1 Shrinkage Porosity: The shrinkage that occurs during solidification is the primary source of porosity formation in aluminum castings. In most aluminum cast alloys, the volume shrinkage varies typically from 5 to 8%. Shrinkage porosity also occurs on a "micro" level as "microshrinkage" or "microporosity", which is dispersed in the interstices of dendritic solidification regions, typically found in alloys with large solidification ranges.

2.5.1.2 Gas Porosity: The other main source of porosity arises from gas evolution resulting from a decrease in the solubility of the gas during solidification of the liquid metal, for example, for hydrogen gas in aluminum. The gas rejected can nucleate both in the liquid metal during solidification, and in the solid immediately afterwards, giving rise to two very different kinds of porosity, termed interdendritic (or primary) porosity and secondary porosity, respectively. These effects are typically exhibited by hydrogen in

aluminum. Porosity is harmful to alloy strength and ductility. Although the maximum pore size parameter best characterizes the porosity-tensile property relationships, No definite correlation between porosity and YS was established. Fairly good linear correlations are obtained between log UTS and log El% for all alloys, experimental or industrial, under all conditions. Porosity in castings is always detrimental to mechanical properties.

Thomas and Gruzleski have observed that for a given alloy and specific solidification conditions, there is a "threshold hydrogen content" below which no primary porosity is formed and that the tendency for porosity formation is reduced with an increase in cooling rate and a decrease in the alloy freezing range.[THO 1978]

Pehlke studied that the nucleation of gas porosity is found to take place at the base of α -Al dendrite arms, Figure (2.5a). The synergism (between the shrinkage and gas

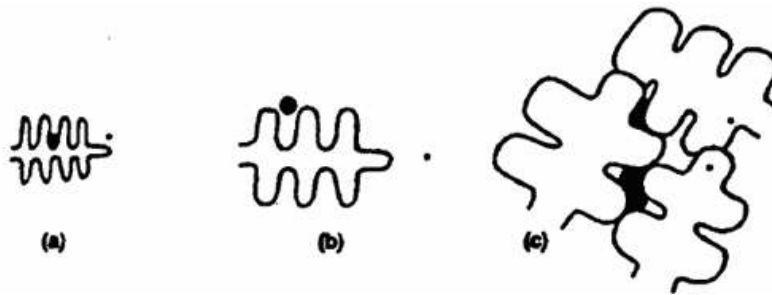


Fig 2.6 Growth Process of porosity formation

porosities) which, surmounts the large negative free energy required to form a gas-metal surface, makes such a process easier. With the progress of solidification, porosity growth is observed due to the higher potential for gas evolution. Such growth makes the radius of the porosity large enough to overcome the gas-metal interfacial energies, eventually leading to the detachment of porosity from the dendrite, Figure (2.6b) Convective forces also play a role in such detachment. With the further progress of solidification, collision happens among neighboring dendrites, making it difficult for interdendritic feeding. Therefore, porosity growth is thought to be necessary for the compensation of

solidification shrinkage Figure (2.6c). It seems that the simultaneous occurrence of shrinkage and gas evolution is essential to the formation of porosity defects.[PEH 1985]

Iwahori et al studied the effect of Alloying Elements on Porosity Formation the process of solidification in Al-Si alloy castings containing various levels of silicon. They found that with increasing silicon content, shrinkage porosity was more likely to occur, but could be controlled by increasing the cross-section area of the riser neck of the casting mold.[IWA 1995]

Chen and Engler made a quantitative analysis of the effect of silicon concentration on porosity formation. They reported that silicon affects porosity formation by changing the mode of solidification. As silicon is added to pure aluminum, pore formation is increasingly favored by the spongy dendritic solidification caused by the increase in silicon content. As the eutectic composition is approached, the tendency for porosity formation decreases, due to the decrease in freezing range and resultant lack of a dendritic structure. Roy et al. observed that copper in Al-Si alloys is present as CuAl_2 or in a complex form. The CuAl_2 phase particles may assist in pore formation.[CHE 1991]

Fang and Granger studied the effect of cooling rate on porosity Formation have shown that for a given melt hydrogen content, an increase in the cooling rate decreases both the total amount of porosity volume fraction) and the average pore size (equivalent average pore diameter)[FAN 1999].

Radhakrishna et al have reported that the relationships obtained between porosity and the three tensile properties (UTS, YS and El%) are nonlinear. The shape of such nonlinear graphs gives an indication of the pronounced influence of porosity on the properties, especially at lower porosity levels. Even an increase of about 0.5 vol pet in the porosity value can bring down the strength and ductility to dangerously low levels. Among the properties measured, UTS seems to be the one most affected by porosity, followed by YS and El%. According to him Thus, it is generally accepted that the failure or fracture occurs in three stages: (i) silicon particle cracking at low plastic strains (1-2%); (ii) as deformation proceeds, cracked particles generate localized shear bands which

form microcracks by joining adjacent cracked particles; and (iii) microcrack coalescence followed by propagation, leading to final fracture.[RAD 1981].

Choong Do Lee studied on Al–10%Si–2%Cu and explained the effect of micro-void and shrinkage hole on tensile properties. He explained that the area fraction of micro-voids was measured through fractography analyses by scanning electron microscope (SEM) observation on fractured surface for entire tensile specimens. And, the area fraction of micro-voids was expressed as an area ratio of total area of the micro-voids to entire fractured surface. He conclude that The overall tensile properties of alloys are depended practically on the high volume fraction and anisotropic damage of Si-particle, rather than the area fraction of micro-voids only and also show that the defect susceptibility of both alloys depends practically on the effective internal void area, rather than that of microvoids only [CHO 2008].

J.Y. Hwang studied the microstructure and mechanical properties of Al-Si-Cu 319 aluminum casting alloys. The microstructures of the four different samples used in these experiments consist of aluminum dendrites, eutectic silicon, iron, copper-containing intermetallic phases, and porosity. The as-cast microstructures of alloy demonstrate that, while the aluminum dendrites have little variation in size and dendrite arm spacing (DAS), the interdendritic regions display considerable variations in the size, shape, and distribution of the intermetallic phases as well as in the amount of porosity. And he observed surfaces that separate the exposed porosity appear to have been formed by brittle cleavage from the porosity and secondary dendrites and propagate through the interdendritic phases and porosity.[HWA 2008]

Surappa et al studied the Porosity measurements are generally carried out by image analysis from direct measurements on metallographic surfaces; such measurements give average porosity from locally limited areas and may not reflect the magnitude of the effects of porosity on mechanical properties. The porosity exposed on the fracture surfaces should provide more relevant information related to its effect on tensile properties as reported. [SUR 1986]

Dighe et al. had performed the systematic research studies on the fracture mechanism of Si-particle in terms of the variation of loading condition and strain rate. They reported that the relative contribution of the debonding and cracking of Si particle to the total damage strongly depend on the stress state by loading condition, and the anisotropic damage of Si-particle depends sensitively on the loading condition.[DIG 1997]

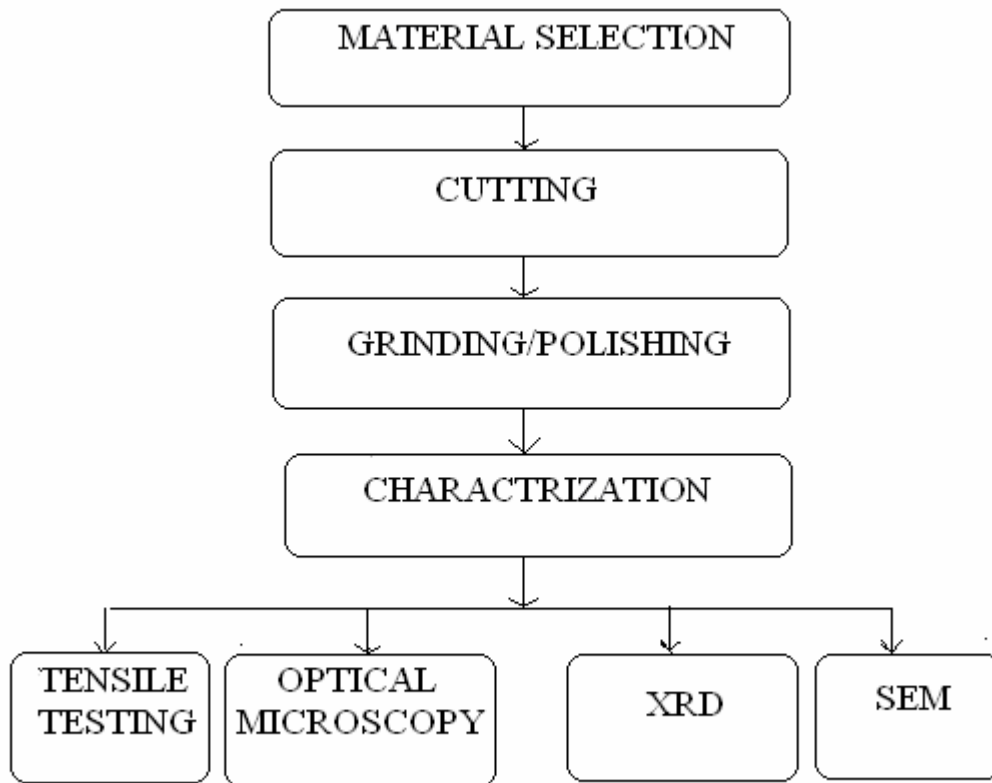
Duwez studied the microstructure of Al-8wt%Si, Al-12wt%Si and Al-16wt% Si. According to him Optical micrographs of ingot Al-8wt% Si alloy are given similar microstructures with a non-uniform distribution of needle-like Si particles in the matrix of α -Al. The micrographs of Al- 12wt% Si alloy, also showed similar microstructure as Al-8wt% Si, except with increasing Si concentration. Similar results have been reported elsewhere Al-16wt% Si alloy exhibits not only needle-like eutectic Si phase but also large faceted massive primary Si crystals that signify a hypereutectic microstructure.[DUW 1980]

Horstemeyer et al proposed the nucleation and coalescence model of voids and cracks for ductile material with second phase. In their studies, the void-crack nucleation model was described as a function of the fracture toughness of aggregated material, the size and volume fraction of second phase, and the stress and strain level. According to him the crack initiation of Si-particle in Al-Si alloy can be achieved even in extremely low strain region, and this induces eventually the premature fracture with severe plastic deformation of Al-rich matrix neighbor to Si-particle by stress concentration. Thus, the fracture damage of anisotropic Si-particle can be considered as a primary source dominating the overall tensile properties of Al-Si alloy, together with the variation of the area fraction of micro-voids. [HER 1990]

In this chapter all the details about the preparation and characterization of samples has been described. In the present work, the casting technique has been utilized to prepare the samples of aluminum alloys. The experiment technique involves following steps:

- Synthesizing
- Preparation of samples
- Characterization & Testing

Process Flow Chart



3.1 Details of raw materials

A brief description of the raw materials used in the synthesis of composite is presented as follows:

3.1.1 Matrix material

Commercially pure aluminum alloys was used as a base metal in the present work. Copper with 99.9% purity and silicon 99.99% was used as an alloying element.

The final composition of the master alloy prepared is shown in Table 3.1 and 3.2

Table 3.1 Chemical composition of Al-Cu master alloy:-

Element	Si	Cu	Fe	Mn	Cr	Mg	Al
Wt%	.13	18	.30	.07	0.01	0.03	81.5

Table 3.2 Chemical composition of Al-Si master alloy

Element	Si	Cu	Fe	Mn	Cr	Mg	Al
Wt%	24.1	.03	.54	.07	0.01	0.03	75.32

3.1.1.1 Chemical analysis of aluminum-Copper master alloy

Turnings were collected from the as-cast alloy for chemical analysis by machining. Procedure of chemical analysis for estimation of Cu present in the cast alloy is as follows:

One gram Al-Cu powder was weighed and put inside a fuming hood. A little amount of concentrated HNO₃ acid was added till complete dissolution was achieved. About 5ml of concentrated H₂SO₄ was added and the solution was heated till it got dried. The dried paste was then cooled to room temperature and was re-dissolved in distill water. The solution was then filtered. 100ml solution was then taken and an adequate amount of NH₄OH was added followed by addition of acetic acid. The solution was cooled and potassium Iodide (10g) was added and stirred till color light yellow, followed by the addition of starch indicator. The solution was titrated with Sodium thiosulphate till it became colorless. Burette reading of Na₂S₂O₃ consumed was used to calculate the amount of copper in the alloy by the following formulae.

$$\% \text{ Cu} = 0.0063 \times \text{Na}_2\text{S}_2\text{O}_3 \text{ consumed}$$

3.1.1.2 Chemical analysis of aluminum-Silicon master alloy

Turnings were collected from the as-cast alloy for chemical analysis by machining. Procedure of chemical analysis for estimation of Si present in the cast alloy is as follows:

One gram Al-Si powder has been weighed. A little amount of concentrated HCl, HNO₃ (HCl: HNO₃ = 1:2) and water was added to dissolve the alloy. The solution was then heated to about 540⁰C till precipitates were formed. The precipitates were filtered and wash with distil water for 2-3 minutes. We have taken 5ml of concentrated gel which was heated at the 580⁰C and leave it till dry the sample. The remaining amount is Silica Weight the silica and read the weight of Silica.

3.2 Synthesis

Alloys were synthesized with the help of liquid metallurgy. The Important process parameters of synthesized alloys were amount, melting and pouring temperature, mould type and size. The synthesized alloys composition as described below.

i)- Al- 12wt%Si-2.5wt% Cu

ii)- Al- 11wt%Si-3.5wt% Cu

iii)- Al- 10wt%Si-4.5wt% Cu

The synthesis of aluminum alloys castings have been done by the following method.

3.3 Table of calculated weight of three alloys

Alloy composition (wt%)	Al-Si Master alloy (in gm)	Al-Cu Master alloy (in gm)	Pure Aluminum (in gm)
Al-12wt%Si-2.5wt%Cu	10.42	41.38	48.21
Al-11wt%Si-3.5wt%Cu	37.13	14.58	47.18
Al-10wt%Si-4.5wt%Cu	18.75	34.48	46.77

For preparing the three Al-Si-Cu alloys as tabulated (table: 3.3). The calculated amount Al-Cu master alloy, of Al-Si master alloy and Al was kept in the fine graphite crucible. The crucible with the metal charged was placed into the muffle furnace, which was heated upto 750°C and metal was allowed to melt. Stirring was done with the help of iron rod by hand for the mixing of charge. When charge was melted then removed it from the furnace and poured into iron mould and allowed the metal to cool and solidified in the shape of the mould. The as-cast sample was taken out of mould.



Fig 3.2 Muffle Furnace

3.3 Sample preparation

3.3.1 Grinding/polishing

The samples have been metallographically grinded and polished. The polished samples have been etched by killer's Reagent for optical microscopy.

3.3.2 Preparation of the tensile samples of Al-10wt% Si -4.5wt%Cu, Al-11wt% Si - 3.5wt%Cu Al-12wt% Si -2.5wt%Cu alloy.

For tensile testing of Al-Si-Cu alloys, prepared samples have been prepared by lathe machine as shown in figure 3.3. The diameters of the sample prepared are between 6-7mm and length L_0 is upto 18-19mm.

Standard tensile test specimen

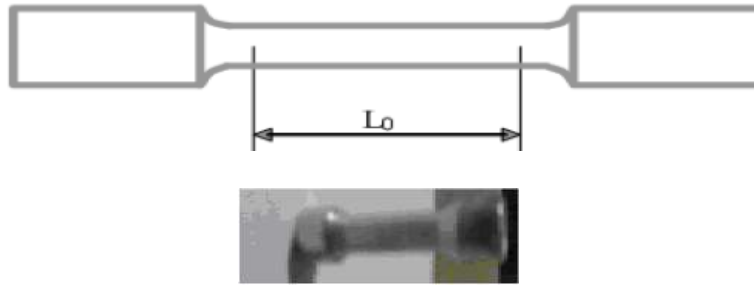


Fig 3.3 standard tensile samples

3.3.3 Tensile testing of the Al-10wt% Si -4.5wt%Cu, Al-11wt% Si -3.5wt%Cu, and Al-12wt% Si-2.5wt%Cu alloy material

Tensile testing of the of all three samples have been accomplished by the help of tensometer as shown in figure 3.4



Fig. 3.4 Tensometer for tensile testing

3.4 Microstructure characterization

The well-polished samples were then observed under an optical microscope. Micrographs were taken with the help of CCD camera attached to the optical microscope.

3.5 X-Ray Diffraction Technique

The X-ray diffraction patterns were recorded using Rigaku model Geiger diffractogram with $\text{CuK}\alpha$ radiation ($\lambda = 1.5418\text{\AA}$) obtained from copper target using an in built Ni

filter. The 2θ values for XRD patterns were generally taken in the range of 5° to 90° for most of the samples at a scan speed of $5^\circ/\text{min}$.

3.6 Fractography

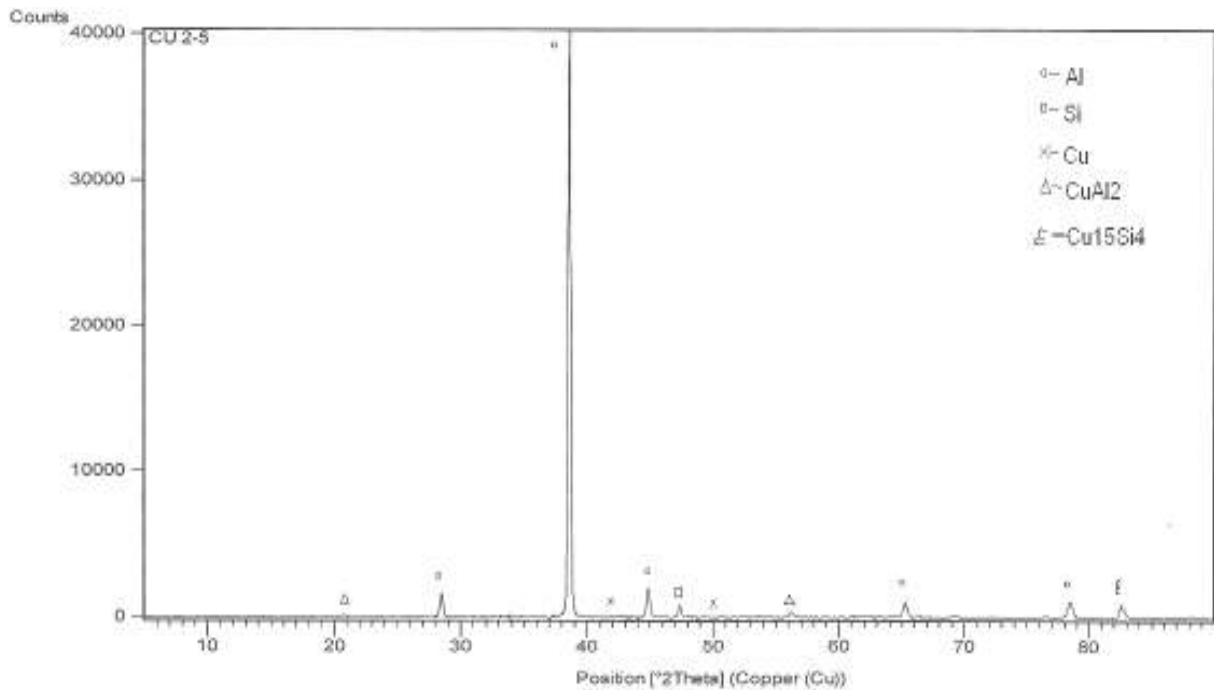
Fracture surfaces of tensile-tested samples were examined in order to determine the crack initiation and propagation behavior of the cast alloys. Samples have been taken from the fracture surface and observed under SEM. Extra care was taken during the cutting to avoid contamination of the fracture surface. The bottom of the sample has been flattened and then mounted on a standard base with special glue. The Scanning Electron Microscope operated at 15 kV.

4.1 Synthesis

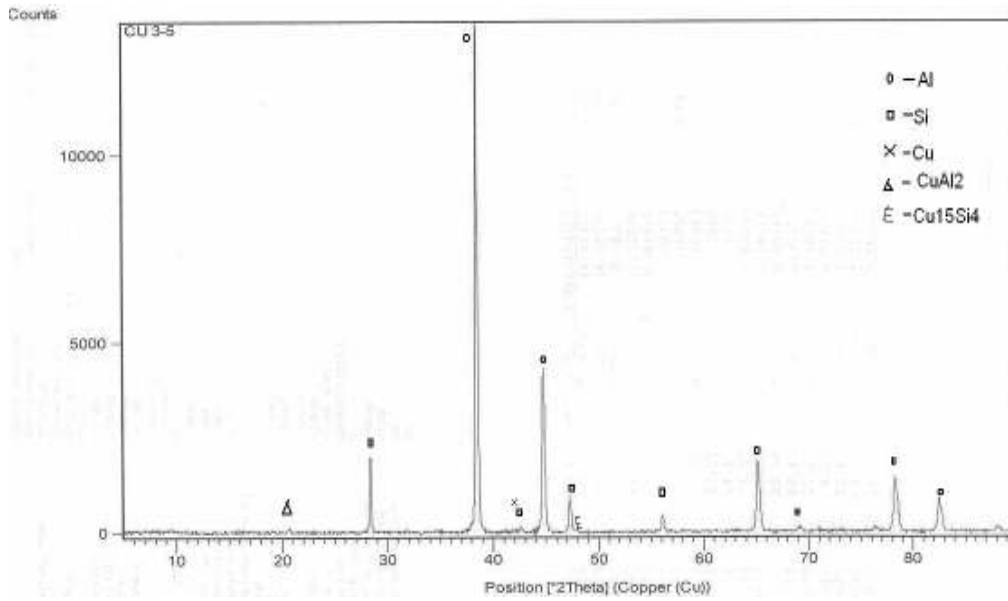
Syntheses of all the alloys have been done by casting route. Though care was taken to eliminate blowholes and other porosity by heating the mould, but gas evaluation during porosity has been observed. It can be due to higher moisture contact in the atmosphere during rainy season.

4.2 X- Ray diffraction analysis

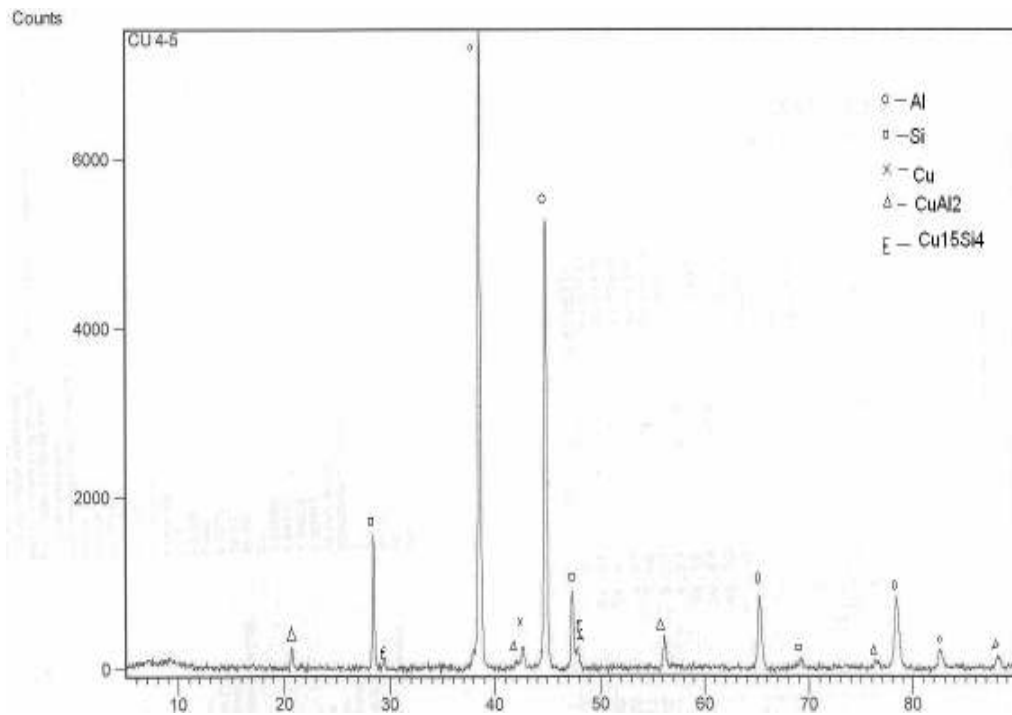
Figures 4.1-a,b and c shows the XRD results of as cast samples. All three alloys conform the presence of alloying elements like Si, Cu and different phases like CuAl_2 , $\text{Cu}_{15}\text{Si}_4$ for all the alloys.



(a)



(b)



(c)

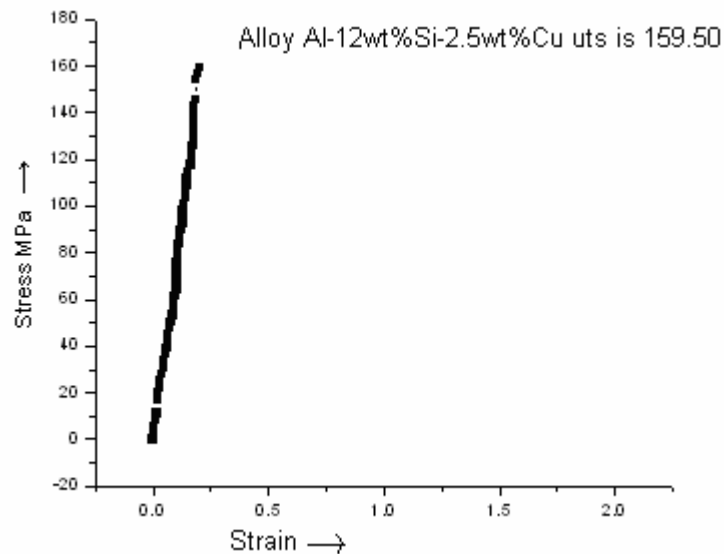
Fig. 4.1 – X-ray diffraction pattern of (a) Al- 12 wt%Si-2.5wt%Cu alloy (b) Al- 11 wt%Si-3.5wt%Cu alloy (c) Al- 10 wt%Si-4.5wt%Cu alloy

4.3 Tensile Testing results

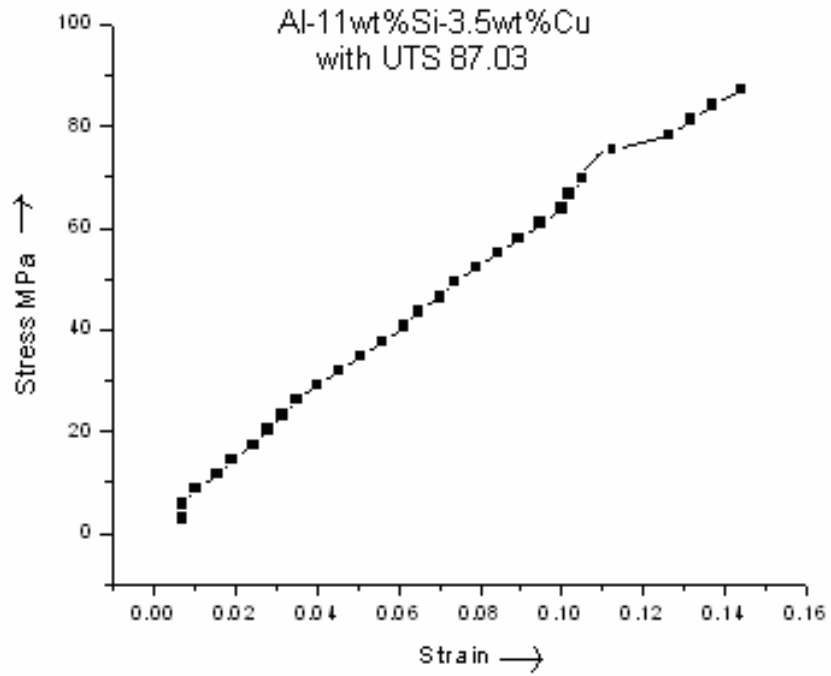
Tensile testing was done with the help of tensometer and the results of all three alloys explained below.

4.3.1 Tensile testing of Al-12wt%Si-2.5wt%Cu, Al-11wt%Si-3.5wt%Cu and Al-10wt%Si-4.5wt%Cu alloys

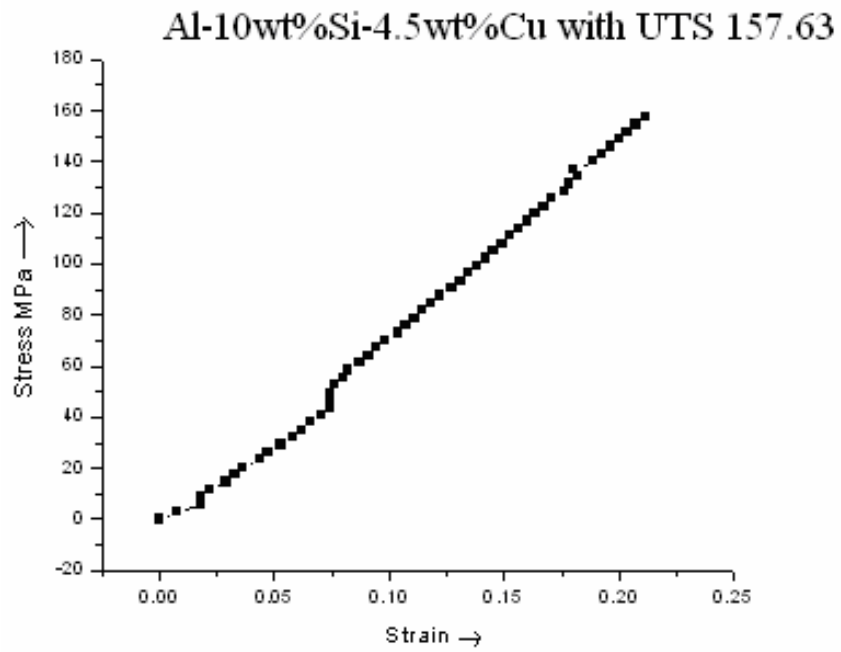
Fig. 4.6(a, b, c) indicate the stress-strain curve of as cast, Al-12wt%Si-2.5wt%Cu, Al-11wt%Si-3.5wt%Cu and Al-10wt%Si-4.5wt%Cu alloys respectively. Observed UTS (ultimate tensile strength) values of, as cast alloys are 159.50MPa, 87.03MPa and 157.63MPa, which is comparatively less than standard value 240MPa. While comparing alloys contradictorily results are observed in these alloys. The reason for this results is been explained by fracture surface studies.



(a)



(b)

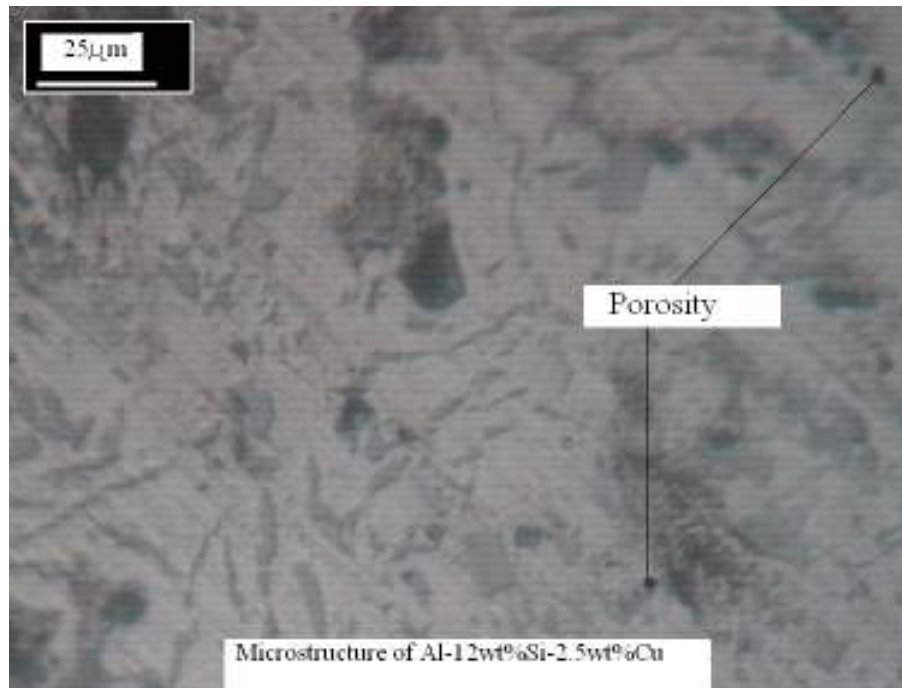


(c)

Fig 4.2 Stress-strain graph of (a) Al- 12 wt%Si-2.5wt%Cu alloy (b) Al- 11 wt%Si-3.5wt%Cu alloy (c) Al- 10 wt%Si-4.5wt%Cu alloy

4.4 Optical microstructures

Fig. 4.3 shows the optical microstructures of as-cast Al- 12 wt%Si-2.5wt%Cu, Al- 11 wt%Si-3.5wt%Cu, and Al- 10 wt%Si-4.5wt%Cu alloys. Flake like structures are observed in all the microstructures. This might be the primary silicon formed during synthesis process.



(a)



(b)



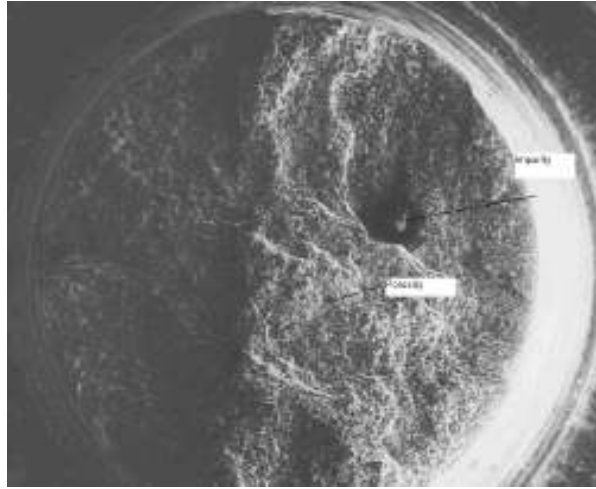
(c)

Fig 4.3- Optical micrographs at 400X (a) Al-12wt% Si -2.5wt%Cu alloy (b) Al-11wt%Si -3.5wt%Cu alloy (c) Al-10wt% Si -4.5wt%Cu alloy

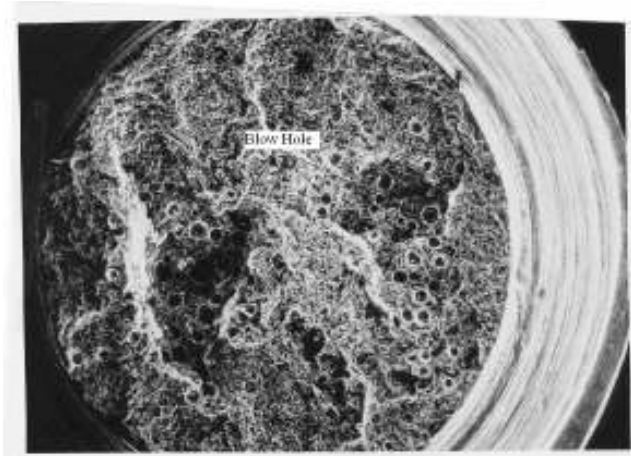
4.5 Scanning electron microstructures

4.5.1 Macrostructural study

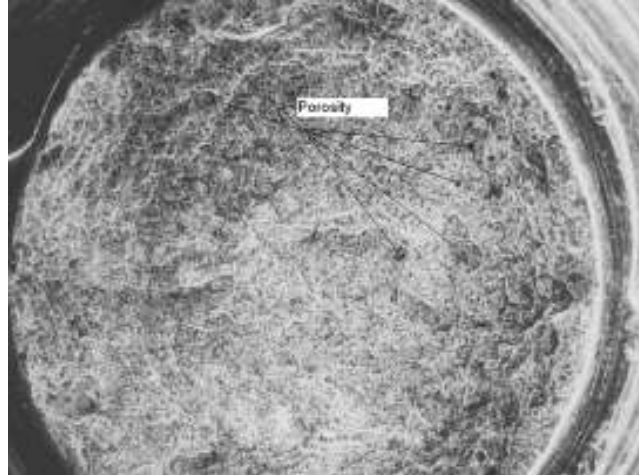
Fig. 4.4 shows the SEM macrostructures of as-cast Al- 12 wt%Si-2.5wt%Cu, Al- 11 wt%Si-3.5wt%Cu, and Al- 10 wt%Si-4.5wt%Cu alloys. An inclusion is observed in Fig. 4.4(a), which might come from crucible during melting operation. Fig. 4.4(b-c) shows the presence of blowhole, uniformly through out the surface. Al- 10 wt%Si-4.5wt%Cu alloy shows less amount of blow hole compared to Al- 11 wt%Si-3.5wt%Cu alloy.



(a)



(b)

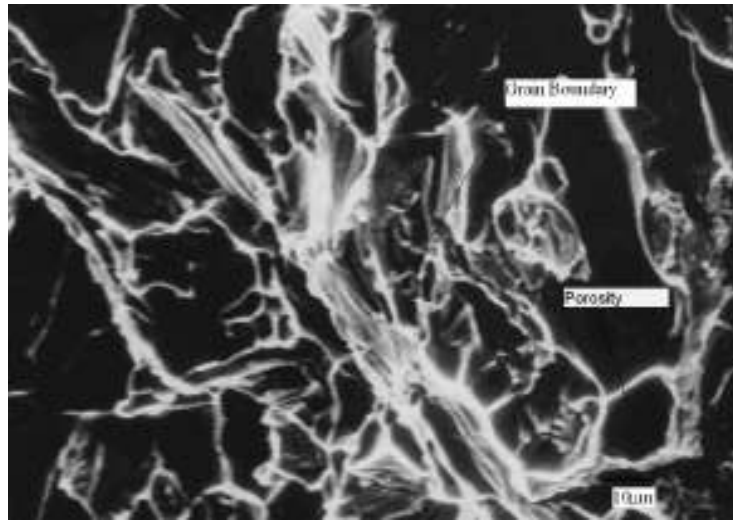


(c)

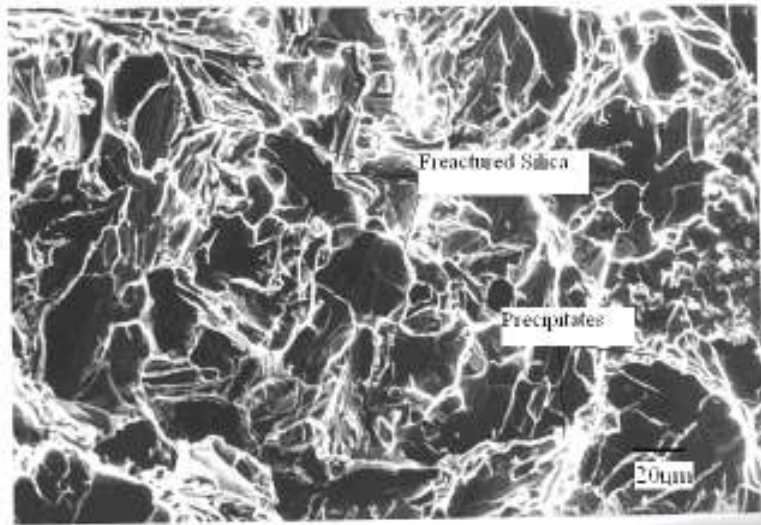
Fig. 4.4- SEM Macrograph at 10X – a) (a) Al-12wt% Si -2.5wt%Cu alloy (b) Al-11wt%Si -3.5wt%Cu alloy (c) Al-10wt% Si -4.5wt%Cu alloy

4.5.2 Microstructural studies

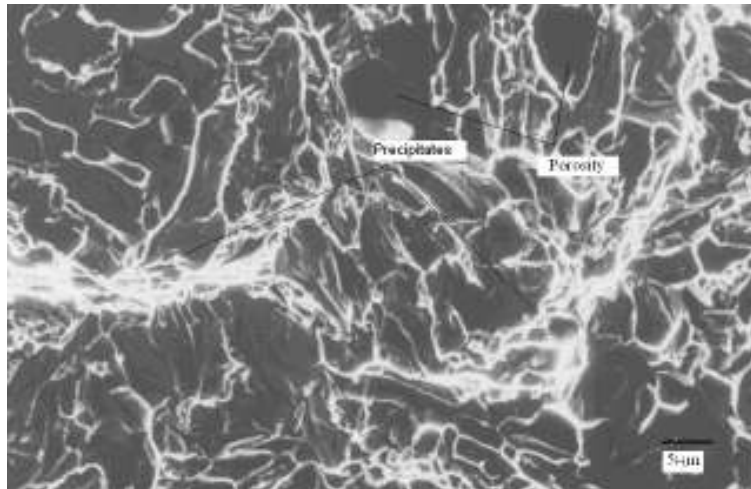
Fig. 4.5 (a, b, c, d) shows the SEM microstructures of as-cast Al- 12 wt%Si-2.5wt%Cu, Al- 11 wt%Si-3.5wt%Cu, and Al- 10 wt%Si-4.5wt%Cu alloys. Fig 4.5 (a) indicates the white grain region might be the grain boundary and plastic deformed porosity, which has non-uniform ductile dimples. Porosities might be the probable site for crack initiation and fracture. Fig 4.5(b) clearly shows the broken silica and cleavage formation, which indicates that the mode of failure is mainly by brittle fracture. Fig. 4.5 (c) shows the presence of porosity and Fig. 4.5 (d) shows the presence of broken silica. SEM micrograph explains that, on the application of tensile load the alloys start fracturing near pores and silicon particles, as these regions are stress concentrated regions. So the alloys show low strength and brittle failure.



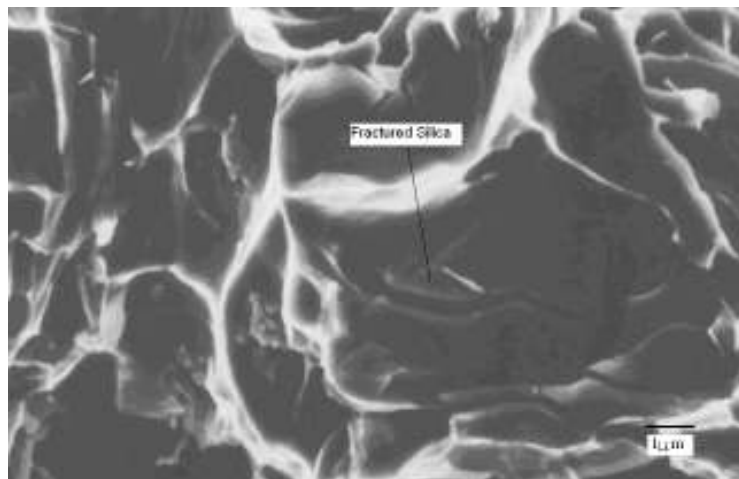
(a)



(b)



(c)



(d)

Fig. 4.5- SEM Micrograph (a) Al-12wt% Si -2.5wt%Cu alloy at 1400X (b) Al-11wt%Si - 3.5wt%Cu alloy at 550X (c) Al-10wt% Si -4.5wt%Cu alloy at 2000X (d) Al-10wt%Si- 4.5wt%Cu at 4300X.

The goal of preparation of alloys was to comparison of the strength of alloys. But due to the casting defect like blowholes, inclusion, and porosities, the tensile strength results were deviated from standard values.

The following conclusions are made from the present investigation:

- 1- The strength of Al-Si-Cu alloy depend upon its alloying elements however in the present investigation volume fraction of porosity, inclusion are responsible for poor strength of the alloy.
- 2- The main reason of porosity is due to gas entrapment (blowholes).
- 3- Fraction of the alloy samples before reaching UTS is due to presence of porosity, which might be the probable crack nucleation region.
- 4- All alloys in the present work have failed by brittle mode as cleavages are observed in SEM of fracture surfaces.
- 5- The composition evaluation was not carried out by phase diagram studies and it might be also a reason for low strength of alloy.

CHAPTER 6

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