EFFECT OF COPPER ADDITION ON THE MICROSTRUCTURE AND MECHANICAL PROPERTIES OF Al-Si ALLOY

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ABSTRACT

Aluminum alloys are very important in many industrial applications because of their lights weight and good mechanical properties. There is a great need to recycle the metals and alloys used in the metallurgical industry and various engineering applications, particularly aluminum alloys due to their low melting point and usefulness. In this work, the effect of copper wires addition with different percent on the microstructure and mechanical properties of Al-Si alloy (piston part as a scrape) were studied. Tensile test, hardness, microstructure SEM and XRD were conducted .The results showed that the addition of copper to the alloy (Al-12wt%Si) have improved its mechanical properties (tensile strength, yield strength and hardness) also changed microstructure of Al-Si alloy as compared with the base alloy.

Keywords: Al-Si alloys, mechanical test, microstructure.

تأثير اضافة النحاس على البنية المجهرية والخواص الميكانيكية لسبيكة Al-Si.

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الخلاصة

تعتبر سبائك الألومنيوم مهمة جدا في العديد من التطبيقات الصناعية بسبب وزنها الخفيف وخصائصها الميكانيكية الجيدة. هنالك حاجة ماسة لإعادة تدوير المعادن والسبائك المستخدمة في الصناعات المعدنية والتطبيقات الهندسية المختلفة، وخاصة سبائك الألومنيوم بسبب درجة انصهارها المنخفضة واستخداماتها. في هذا البحث تم دراسة تاثير اضافة معدن النحاس على شكل اسلاك بنسب مختلفة على البنية المجهرية والخواص الميكانيكة لسبيكة Al-Si والتي اخذت من مكابس احتراق داخلي لمكائن السيارات (خردة). تم اجراء اختبار الشد والصلادة وكذلك فحص البنية المجهرية باستخدام المجهر الضوئي و فحص حيود الاشعة السينية والفحص باستخدام المجهر الالكتروني الماسح. بينت النتائج ان اضافة النحاس الى سبيكة Al-12wt%Si قد حسنت الخواص الميكانيكية (مقاومة الشد, مقاومة الخضوع والصلادة) وكذلك تغيرت البنية المجهرية مقارنة بالسبيكة الاساس.

INTRODUCTION

In recent years, the plenty of waste of aluminum alloys increase, therefore as replacing primary alloys are secondary (recycled) aluminum alloys used. Application of secondary aluminum alloys is important, because the production of primary aluminum alloys consume about 45 kWh/kg of metal and the production of secondary only about 2.8 kWh/kg of metal. It is to the aluminum industry's advantage to maximize the amount of recycled metal, for both the energy-savings and the reduction of dependence upon overseas sources. Utilization of secondary aluminum alloys increase in recent years also due to their comparable properties with primary aluminum alloys [1, 2].

Aluminium-Silicon based alloys are well-known casting alloys with high wear resistance, low thermal expansion coefficient, outstanding castability, together with their low specific weight, good corrosion resistance, and improved mechanical properties in a wide range of temperature. These properties lead to an increasing the applications of Al-Si alloys in automotive industry, especially for cylinder blocks, cylinder heads, pistons and valve lifters [3, 4]. The automotive and aircraft industrial needs led to increasing application of Al-Si cast alloys thanks to the great potential of these materials as replacements for heavier materials (steel, cast iron etc.) [5, 6, 7]. These alloys have between 10 and 13% silicon, and consist mainly of Al-Si eutectic in the cast structure [8].

The mechanical and microstructural properties of aluminum cast alloys depend on the composition; melting conditions, solidification rate, casting process and the applied thermal treatment [1, 9]. Mechanical properties of Al-Si alloys are of course related to the morphology of silicon particles (size, shape and distribution), Al grain size, shape, and dendrite parameters [10]. The presence of additional elements in the Al-Si alloys allows many complex intermetallic phases to form. Copper is a potent precipitation-strengthening agent in aluminum. Cu additions up to about 5% lead to alloys with high strength and good toughness when subject to natural or artificial aging. The addition of Cu increases considerably the strength of Al–Si alloys, due to precipitation of dispersed Al_2Cu (θ) phase during aging. The strengthening contribution from precipitation is typically a function of both precipitate size distribution and volume fraction [11].

In the applications where ductility is not of prime importance such as cylinder head, Cu containing variants of these alloy have the distinct advantage of increased strength at high temperatures and therefore are becoming increasingly popular. This alloy is mainly used in casting engine blocks, cylinder heads, pistons and manifolds [12, 13]. The presence of alloying and impurity elements such as (Cu, Mg, Mn, Fe etc.) leads to more complex constituents (including intermetallic compounds) that are characterized by metallographic consequence [14].

Several studies of Al-Si casting alloy have different factors that affect on microstructure and chemical properties, Hurtalová et al (2012) [1] were studied the effect of chemical composition of Al-Si cast alloy on intermetallic phases, Changes of chemical composition of Al-Si cast alloys led to formation different intermetallic phases in these cast alloys. C. H. Caceres et al (2003) [13] were studied the effect of different contents of elements on Al-Si-Cu-Mg casting alloy, the strength of alloys increases with increasing content of Mg and /or Cu. in all cases the ductility decreases as well. A higher content of Fe generally reduces the strength and ductility.

The present work focused on evaluating the effects of the addition of various amounts of copper (0, 1, 2, and 3 wt. %) on mechanical properties (tensile test, hardness, and ductility) and microstructure of recycled pistons alloy (Al-12wt%Si).

EXPERIMENTAL WORK

The materials used in this work were Aluminum – 12wt% Silicon alloy (recycled piston part), the chemical composition is shown in **Table (1)**, and wires of copper. The chemical composition analysis was carried out using (dissolution spectrometer) in a State Company for Examination Engineering and Qualification (Specialist Institute for Mechanical Industry, previously). A 200 gm. of recycled piston alloy was cut into smaller pieces and melted using graphite crucible in an electrical furnace at 750 °C as shown in **Figure (1)**. After melting, one sample was poured without additive, and three other different weight percentages of copper wire were added to the molten alloy (1, 2, and 3 wt.%) the melt is stirred by electrical stirrer using steel rod for 30 seconds to ensure the homogeneity of the molten alloy. Argon gas with flow rate of 1S milliliter/min was used from the beginning of melting process to reduce the oxidation. After the stirring process, the temperature was raised up to 1000 °C and fixed for 15 min to ensure partial melting of the Cu wires. The homogenized melt was poured in a preheated stainless steel die with dimensions of (17 mm) diameter and (120 mm) length.

1. Tensile Test

The tensile specimen's dimensions were produced according to ASTM-E8 as shown in **Figure (2)**. They were tested by an Instron machine with a (20) ton capacity and (1) cm/min cross head speed. Tests were performed at ambient temperature on smooth specimens at a stress ratio R= -1.
Where:
G: Gage length = 45mm.

D: Diameter = 9 mm

R: Radius of fillet = 8 mm

A: Length of reduced section = 54mm.

The mechanical properties (tensile strength, 0.2% proof strength, % of elongation, % of area reduction, and H.V) were evaluated. From stress – strain curve, the values of tensile strength (σ_T), strain (ϵ) and yield strength (by taking the 0.2% of the strain (as a proof strain)) were found for each alloy [15]. The area reduction percent is calculated from the following relationship [16]:

$$R.A\ \% = (A_o - A) / A_o \quad (1)$$

To find A for equation:

$$A_o * L_o = A * L \quad (2)$$

To find L for equation:

$$\text{Strain } (\epsilon) = (L - L_o) / L_o \quad (3)$$

Where:
R.A: Reduction area (mm^2).
A_o: Original area (mm^2).

A: Final Area (mm^2).
L_o: Original length (mm).
L: Final length (mm).

2. Hardness Test.
Vickers macrohardness was measured using diamond pyramid indenter with applied load of 200 gm. for 15 second endurance to measure the hardness (Five hardness values were taken for each sample).

3. Microstructure Examination

Specimens of 5 mm height, and 10 mm diameter were prepared from the section rods, which were left after study the microstructure. One surface of all specimens were initially grinding using a series of waterproof SiC papers (220, 320, 500, 800, 1000) with increasing fineness to remove any of the scratches present through the cutting or any previous process. Finally polishing was carried out on a disc polisher using diamond pastes of 1 µm particle size with polishing liquid as a cooling lubricant until the mirror like i.e. scratch free surface was obtained. Polished samples were cleaned with distilled water and alcohol. The prepared samples were etched using Keller's solution for about 30-50s in order to reveal the microstructure with grain boundaries and finally, the polished specimens were taken for optical microscopy. The microstructure of the test samples was examined by optical microscope (100W Carlzeiss Jane, Germany, EP. Type 2) connected to digital camera.

4. Scanning Electron Microscope Test.

Microstructural characterization studies were done to observe the microstructure of sample surface test. This is done by using scanning electron microscope. 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 samples were characterized by (Angstrom) Scanning Electron Microscope (SEM) in Nanotechnology and advanced materials research center / University of Technology.

5. X-Ray Diffraction (XRD) Test.

X-Ray Diffractometer SHIMATZO 6000X was used to study the phase composition of the Al-12wt%Si alloy, with measuring condition as below. This test was done in a State Company for Examination Engineering and Qualification.

Target: Cu, Wave length= 1.5406 A^o, 2Theta range= 0-80 deg.

RESULTS AND DISCUSSION

Microstructure

Microstructural characterization studies were done to observe the microstructure of sample surface test. This is done by using scanning electron microscope. Characterization is done in etched conditions. Etching was done using the Keller's reagent (1 volume part of hydrofluoric acid, 1.5 volume part of hydrochloric acid, 2.5 volume parts of nitric acid and 95 volume parts of water).

Figures from (3-6) shows the scanning electron microscope of Al-12wt%Si alloys without and with additives, **Figure (3)** show the SEM of Al-12wt%Si as cast.

See **Figure (3),** higher levels of Si is observed at the edge of the dendrite, which are also generally having higher overall Si concentrations have coarser microstructures. The result is in agreement with L. Pedersen et al (1998) [17] and A. L. Dons et al (1999) [18] and lately confirmed by hardness measurement confirmed by Seifeddine et al (2007) [9]. For the slowly solidified materials, Si could be diffused from the α-Al matrix to Si particles in the eutectic after solidification. This finding explains further the coarsening and formation of Si bands around the dendrites.

The segregation profiles Cu are shown in **Figures 4, 5 and 6**. As the Cu levels are increased, coarseness of phases such the Al_2Cu phase, embedded in-between the dendrites, both as blocky and as eutectic to be increased, from figure showing. Numerous work has been performed on the distribution and location of these Cu-bearing intermetallic and the current study can only confirm these findings [20].

The reason for the increased coarsenesses of Cu-bearing intermetallics, along with increased Cu additions could be explained, besides the time available for growth, by the ability of the matrix to host elements, as clearly observed in **Figures 4,5 and 6**.

The Cu concentrations in the dendrites seem to be slightly influenced by the solidification rate, with a higher Cu concentration at the dendrite centre and edge for coarser microstructures, which is also supposed to be a result of back diffusion due to the longer solidification time. Cu concentrations in the centre of the dendrites have been reported in the literature, but these results show some variations Qian et al (2003) [21] and Sjölander et al (2011) [20]. Generally, as Cu is added, a ternary eutectic reaction at about 525˚C will occur leading to shrinkage that will not be compensated. Besides, the sample hydrogen activity coefficient might decrease with increasing Cu content and hydrogen solubility decreases, leading to increased porosity [22].

However, there is a direct relationship between the copper content and the reduction in the grain size diameter which it related to the enhancement of the mechanical characteristics of Al-12wt%Si.

The microstructures of Al-12wt%Si-Cu casting alloy are essentially consist of three components; the two main components are primary α-Al solid solution phase and Al-Si eutectic, the third component is intermetallic phases which have the important factor improvement on the mechanical properties of alloys [1, 13].

Figures (7-10) shows the optical microstructure of Al-12wt%Si alloys with different additions of copper. From the figures, homogeneous distribution of the primary silicon particles was clear. **Figure (7)** shows the microstructure of Al-12wt%Si alloy without any addition, which consists of the eutectic silicon as acicular flakes, α-aluminum matrix and the primary silicon particles, **Figure (11)** illustrated the XRD pattern of Al-12wt%Si alloy which shows the peaks of Al and Si. **Figure (8)** shows the microstructure of Al-12wt%Si alloys with 1% copper, also consist of primary silicon particles, α-aluminum matrix, eutectic silicon and intermetallic phases of Al_2Cu. **Figure (9)** shows the microstructure of Al-12wt%Si with 2wt% copper; which consists of the eutectic silicon as acicular flakes, α-aluminum matrix, the primary silicon particles and some intermetallic particles of Al_2Cu. **Figure (10)** shows the microstructure of Al-12wt%Si with 3wt% copper, which consist of the α-aluminum matrix, and intermetallic particles of Al_2Cu, **Figure (12)** illustrated the XRD pattern of Al-12wt%Si-3wt%Cu alloy which shows the peaks of Al and Si and Al_2Cu.

As is known, Copper is partially soluble in α – Al solid solution with a maximum solubility of 5.65 wt% at 550 °C. For alloys with Al to from 1 to 4 wt% copper, Cu-rich intermetallic phase (Al_2Cu) typically form in the structure [12]. Al-Si alloy usually contains a little amount of iron, which plays an important role in the nucleation of the eutectic Si in these alloys.

Tensile & Hardness Test Results

Table (2) illustrates the mechanical properties of Al-12wt%Si recycled alloy without and with different copper additions. After melting and pouring of the recycled alloy, it was found that the tensile strength is (111 MPa) where this value represents the tensile strength of piston recycled alloy (Al-12wt%Si) without any additives, and when adding different amounts of copper to the recycled alloy we notice an increase in tensile strength with increases copper additives percent to the Al-12wt%Si and with higher tensile strength value was (172 Mpa) at 3wt% of copper. We notice that 1 wt% of copper added to the base alloy causes a significant increase in the tensile strength as compared to the base alloy more increase was found with 2 and 3 wt% of copper. Also the yield strength increases with increase the copper content and maximum yield strength (49 Mpa) at 3 wt% of Cu. mechanical properties of the alloys depend on the shape, size and distribution of eutectic silicon, α-Al grains/dendrites and the presence of alloying element in case of Al-Si alloys.

The results of the hardness of the Al-12wt%Si alloy with copper lead to a clear increase in the values of hardness as compared to the base alloy hardness value under the same conditions. The reasons for increasing the hardness in this case is the creation of intermetallic compound phase Al_2Cu. **Table (2)** showed the Vickers hardness of the base as well as other alloys with copper additives. It's found that higher hardness values (66.5 H.V) were obtained with 3 wt% of copper additives as compared with base alloy is value (34.7 H.V).

Figures (13-17) show the influence of percentage copper on mechanical properties of Al-12wt%Si. The tensile strength, yield strength and hardness increase with the increasing copper content as compared with base alloy through the formation of intermetallic phases.

The improvement in the mechanical properties such as tensile strength, yield strength, and hardness as compared with base alloy (Al-12wt%Si) is due to Cu addition. The ductility however (elongation and area reduction decrease with increasing copper additions. the elongation and reduction area are (6.2%) (5.48%) while these values decrease with increasing copper content.

The presence of copper in alloy may be produces intermetallic compounds and this phase impeded the movement of dislocations, as a result the alloy has high tensile strength and hardness. Mechanical properties of Al-12wt%Si recycled alloy dependent on the shape, size and distribution of particles (intermetallic compounds) in the resulted alloy.

CONCLUSION

1. From the scanning electron microscope, the addition copper in Al-12wt% alloy change the microstructure from coarse structure to fine structure.

2. The mechanical behavior of Al-12wt%Si recycled alloys increased with increasing copper content. The tensile strength, yield strength and Vickers hardness increased with increasing copper content. While elongation and reduction area decrease with increase the copper additions to base alloy.

3. The presence of alloying elements such as (Cu, Fe, Mg, Mn) leads to formation intermetallic compounds, presence Al_2Cu phase in microstructure strengthening the Al-12wt%Si alloy.

4. It possible take advantage of the materials or alloys (scrap) by re-melted and the addition of some of the elements that alter mechanical properties and uses in suitable engineering applications.

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Table (1): The chemical composition of the (Al-12wt% Si) recycled alloy.

Si	Pb	Mn	Mg	Zn	Fe	Cu	Ni	Cd	Sn	Ti	Al
12.09	**0.261**	**0.107**	**0.069**	**0.346**	**0.787**	**0.34**	**0.654**	**0.389**	**0.13**	**0.105**	**Balance**

Table (2): Effect of different Cu wire additions on mechanical properties of (Al-12wt%Si) recycled alloy.

Alloy No.	Alloy type	Tensile strength (MPa)	Yield strength (MPa)	Strain	Hardness HV	Elongation %	Reduction Area %
1	Al-12wt%Si	111	20	0.062	34.734	6.2	5.84
2	Al-12wt%Si +1wt%Cu	135	32	0.0595	45.788	5.95	5.62
3	Al-12wt%Si +2wt%Cu	166	44	0.0586	63.0987	5.86	5.53
4	Al-12wt%Si +3wt%Cu	172	49	0.0576	66.5356	5.76	5.45

Figure (1): Illustrated the melting process.

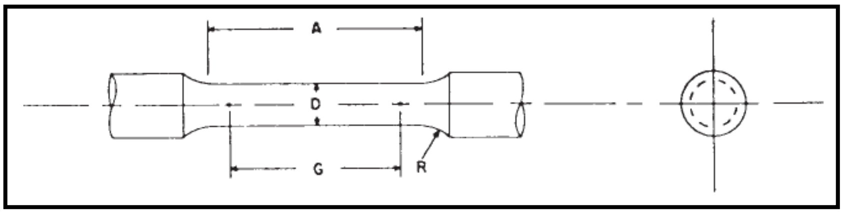

Figure (2): Shows the standard ASTM-E8 of tensile specimen test.

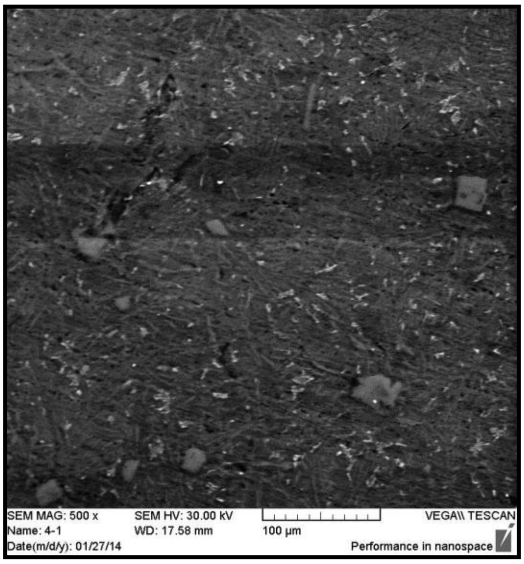

Figure (3): SEM for Al-12wt%Si alloy.

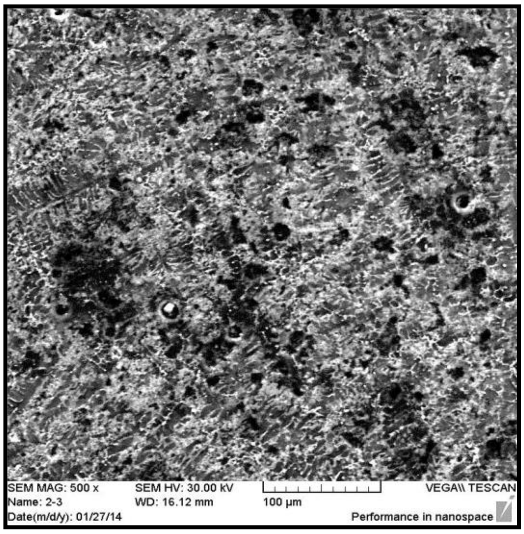

Figure (4): SEM of Al-12wt%Si-1wt%Cu.

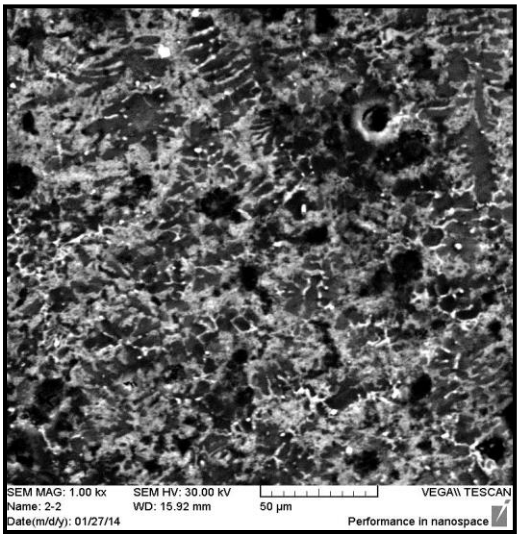

Figure (5): SEM of Al-12wt%Si-2wt%Cu.

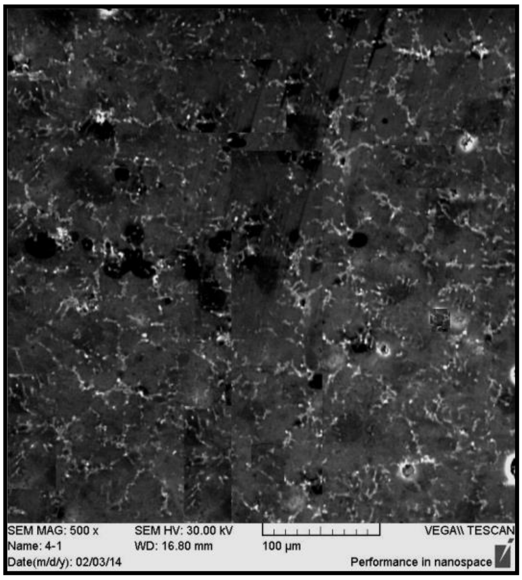

Figure (6): SEM of Al-12wt%Si-3wt%Cu.

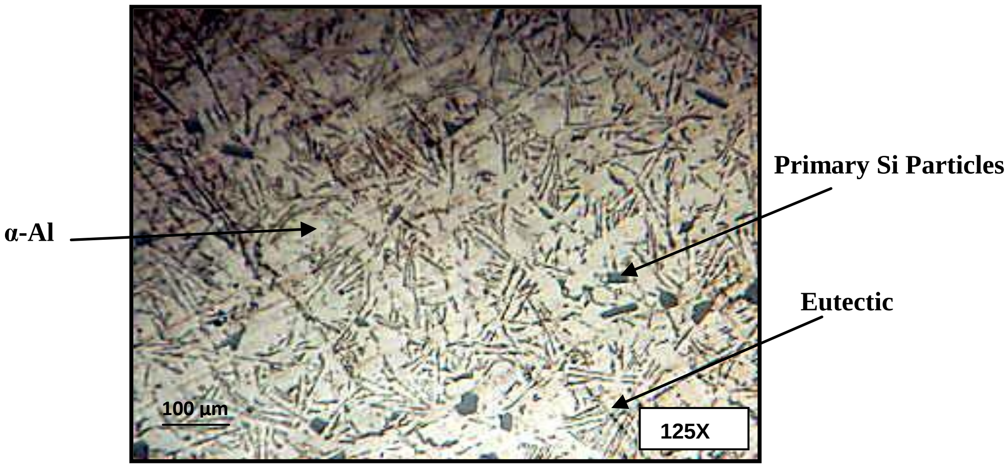

Figure (7): As received microstructure of Al-12wt%Si alloy.

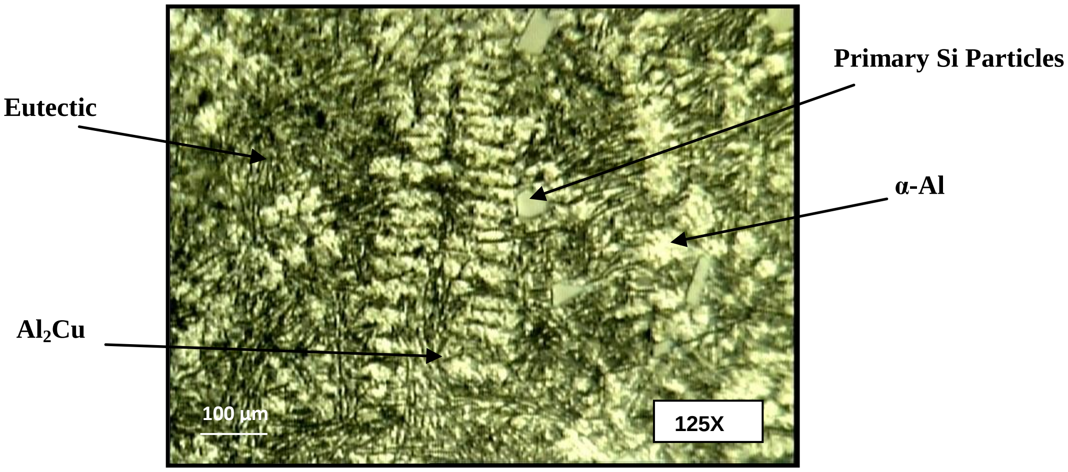

Figure (8): Microstructure of Al-12wt%Si-1wt%Cu.

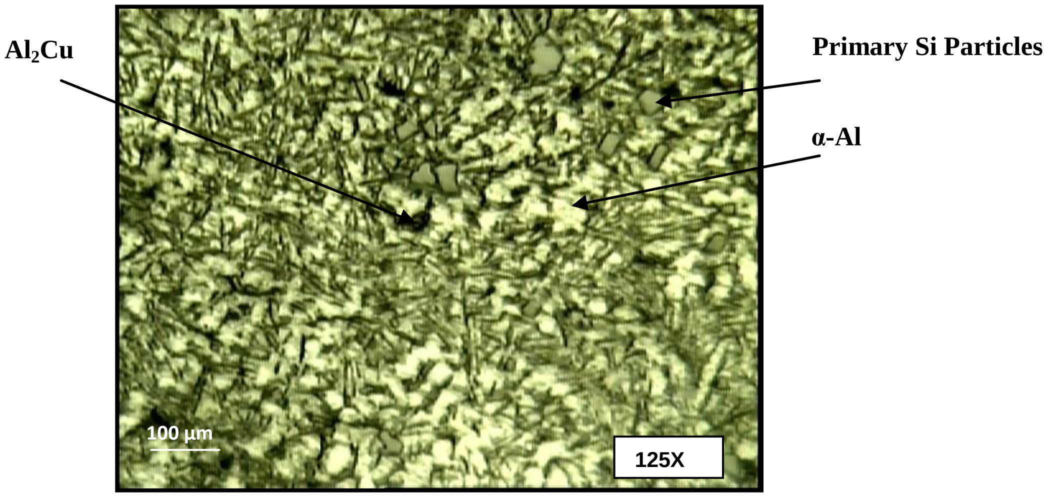

Figure (9): Microstructure of Al-12wt%Si-2wt%Cu.

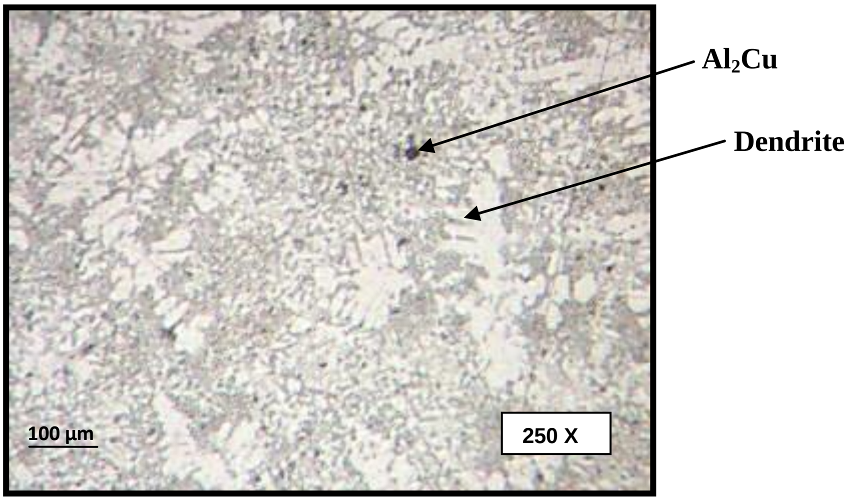

Figure (10): Microstructure of Al-12wt%Si-3wt%Cu.

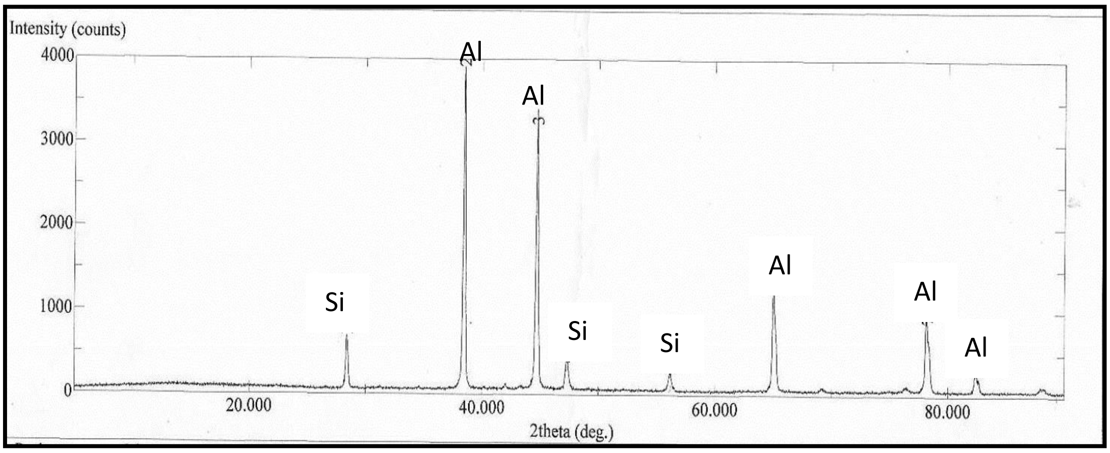

Figure (11): XRD pattern for Al-12wt%Si recycled alloy.

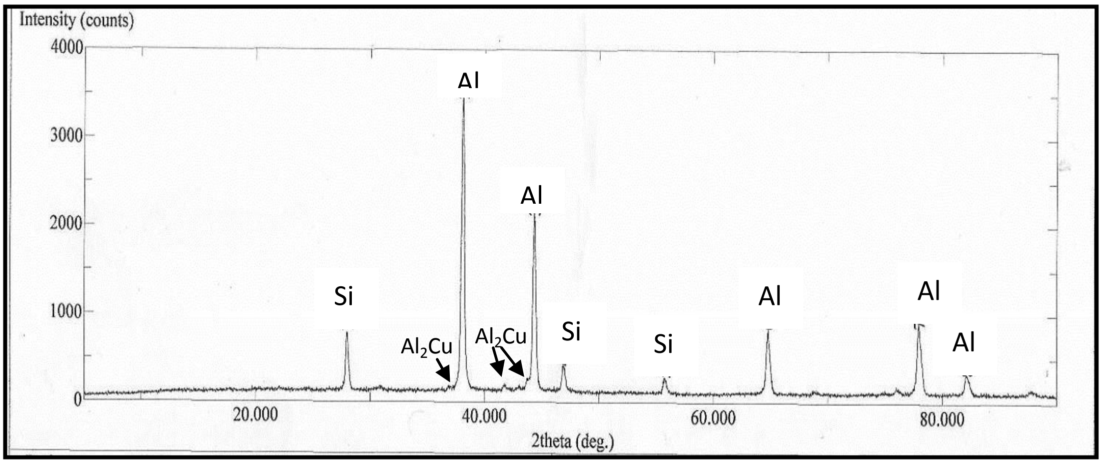

Figure (12): XRD pattern for Al-12wt%Si-3wt%Cu alloy.

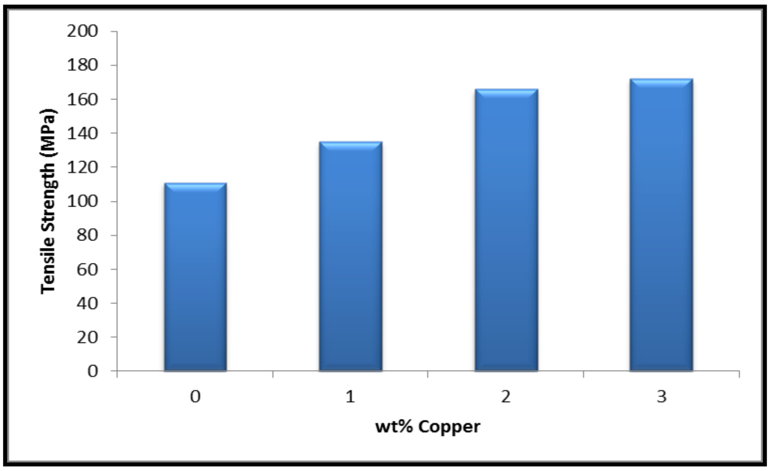

Figure (13): Shows the effect of copper addition on tensile strength of Al-12wt%Si alloy.

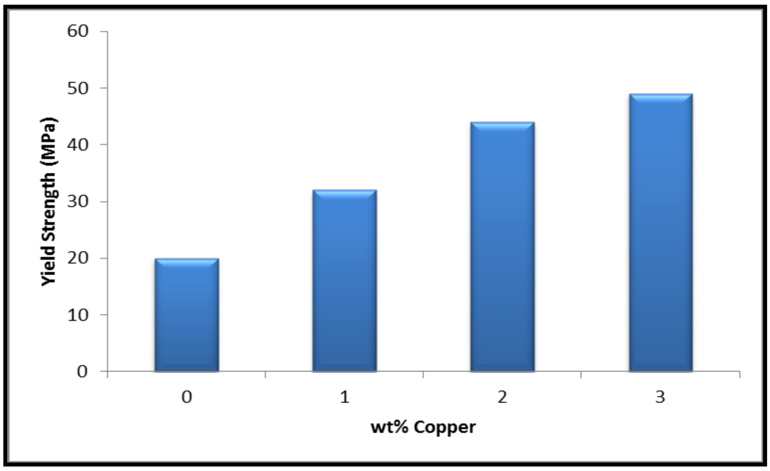

Figure (14): Shows the effect of copper addition on yield strength of Al-12wt%Si alloy.

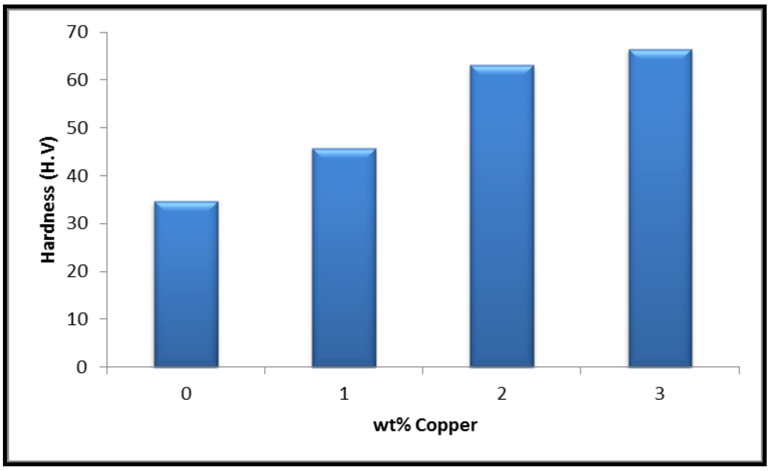

Figure (15): Shows the effect of copper addition on hardness of Al-12wt%Si alloy.

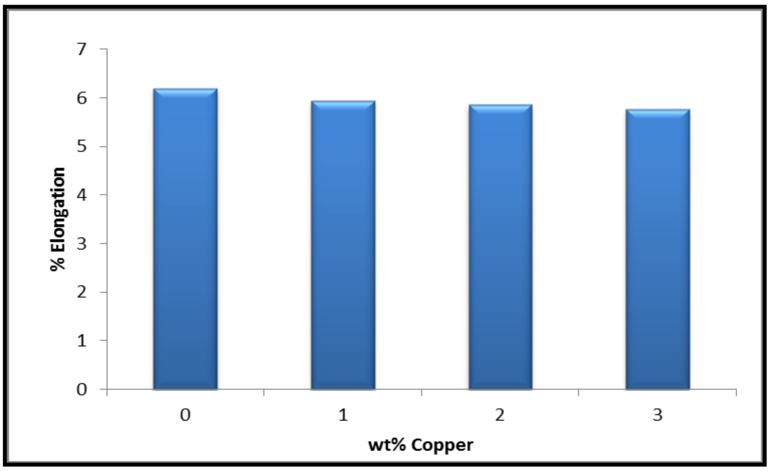

Figure (16): Shows the effect of copper addition on % elongation of Al-12wt%Si alloy.

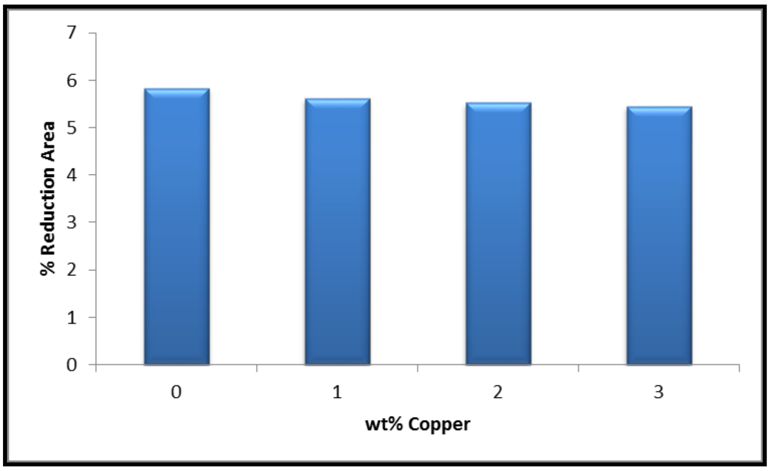

Figure (17): Shows the effect of copper addition on % reduction area of Al-12wt%Si alloy.