Int. j. adv. multidisc. res. stud. 2025; 5(6):1101-1109

Received: 15-10-2025
Accepted: 25-11-2025

International Journal of Advanced Multidisciplinary Research and Studies

ISSN: 2583-049X

Effect of Cerium and Isothermal Treatment on Mechanical Properties and Microstructural Evolution of Al-Si-Mg (A356) Alloy

[1] SB Tajiri, [2] BG Danshehu, [3] UM Jajere, [4] AM Adua, [5] MN Gidado

[1, 2] Mechanical Engineering Department, Faculty of Engineering, Abdullahi Fodio University of Science and Technology, Aliero, Kebbi State, Nigeria

[3, 4] Electrical and Electronics Engineering Department, Faculty of Engineering, Abdullahi Fodio University of Science and Technology, Aliero, Kebbi State, Nigeria

[1, 5] Mechanical Engineering Department, College of Engineering, Umaru Ali Shinkafi Polytechnic, Sokoto, Sokoto State, Nigeria

Corresponding Author: **SB Tajiri**

Abstract

Aluminium has been identified as one of the most used metal in engineering applications owing to some overwhelming properties possessed by the metal. Aluminium in its pure form does not have strong place in engineering application, but when alloyed with other metals and non-metals the properties improved tremendously to the expectation of engineering application. It is alloys have been developed using different elements, such as silicon, copper, magnesium, manganese, zinc, tin, etc, either singly or in combination. Among aluminium alloys, aluminium-silicon alloy are the most used aluminium alloy in various aspects of engineering application, due to its strength, wear resistance, corrosion resistance, castability, fluidity, etc. But, it is prone to brittleness owing to the development of coarse columnar grain structures of eutectic silicon, which reduces the ductility of the alloy. To take care of the formation of the eutectic silicon, certain elements are added in traces in order to change coarse structures formed by the eutectic silicon to fibrous or fine flake structures, which induces ductility back to the alloy. In this paper cerium (rare earth metal) was used as the chemical for modification of the eutectic silicon in the aluminium alloy. After the development of the A356 alloy cerium was added in varied percentages as 0.5; 1.0; 1.5; 2.0; 2.5%Ce. Heat treatment was done on one sample out of each pair of all the composition. Tensile test, Hardness test and microstructural examination (SEM) was carried out. The results show that cerium improved the ductility of the samples, such that there is proportionality in relation to mechanical properties. UTS is 411.78 vs 400.05MPa for 0% cerium heat treated and non-heat treated respectively, while the samples with the highest cerium contents (2.5%Ce) have UTS of 447.86 vs 442.62 for heat treated and non-heat treated respectively. Their hardness (HBN) are 307 (0%), 390 (1.0%) and 439 (2.5%) for heat treated. and 349 (0%), 391 (1.5%) and 459 (2.5%) for non-heat treated. The microstructure was modified with addition of cerium and is even better with heat treatment.

Keywords: Cerium, Eutectic, Isothermal, Hardness, Microstructure, Strength, Tensile

Introduction

Aluminium is the second widely used metal due to its desirable chemical, physical and mechanical properties. It is alloyed with elements like Si, Mg, Cu, Mn, Zn, Sn, Fe, etc. (Mario *et al.*, 2019; Barrirero *et al.*, 2019; Abdulwahab *et al.*, 2011) [30, 9, 1]. Easily recyclable, lightweight, relatively soft, durable, highly workable, high electrical conductivity are some of the properties that make aluminium and its alloy an excellent engineering material. It is equally attracted by its various unique properties; such as appearance, strength-to-weight ratio, excellent thermal properties, workability properties and good mechanical behaviour (Anna *et al.*, 2018 and Abdulwahab *et al,*, 2011) [4, 1].

Aluminium, better used in alloy form, have been identified as an important and useful engineering material with wide range of applications in transportation, packaging, construction, electronics, aerospace among others (Eda and Ali, 2015) [14]. They are widely used for different applications in industries and marine environment because of their excellent properties, such as high strength-to-weight ratios, high thermal conductivity, good corrosion properties and excellent workability (Popoola *et al.*, 2012) [37]. Addition of silicon to aluminium can improve its fluidity as well as castability and mechanical properties (Wang *et al.*, 2016 and Asuke *et al.*, 2012) [47, 6]. Magnesium is the main solid solution strengthener to Al–Si alloy. When added Al-Si-Mg alloy is obtained (Seyedrezai *et al.*, 2009) [41]. A356 alloys is a group of Al–Si–Mg alloys and their increase in strength is by precipitation of Mg_2Si in aluminium matrix (Samuel *et al.*, 2016; Zander and Sandstrom, 2008 and Evren and Bilgehan, 2007) [38, 49, 16]. This precipitation sequence and reactions have long been reported and accepted (Khaled *et al*., 2018 and Samuel *et al.*, 2015 [39]).

Addition of Magnesium to Al-Si alloy improves its strength to weight ratio and yield stress by combining with silicon to form the age hardening phase with the formula Mg2Si, which leads to increase in response to precipitation hardening, from a super saturated solid solution (SSS) during heat treatment, which in turn results in higher yield strength in these alloys (Williams and Tien-Chien, 2017 and Birol, 2009) [48, 10]. However, Al-Si-Mg alloys still exhibit insufficient and poor performance in service condition that requires high hardness, wear resistance and aggressive corrosion environment (Abdulwahab *et al.*, 2012) [2]. Due to different industrial applications and economic importance of aluminium and its alloys, their protection against corrosion by inhibiting the working environment is worth studying (Ayeni *et al.*, 2012; Nnanna *et al.*, 2012) [7, 35].

In the present work, the use of rare earth metals (cerium, samarium, terbium and ytterbium) and isothermal treatment to modify the eutectic silicon in the alloy will be investigated using mechanical, corrosion and microstructure as criteria.

The aim of this research is to investigate the effects of Cerium rare earth metal and isothermal treatment on the mechanical, corrosion properties and microstructural evolution of Al-7%Si-0.3%Mg Alloy.

To achieve the aim, the following objectives are to be pursued:

- To develop Al-7%Si-0.3%Mg alloy with Cerium (Ce) rare earth metals as modifiers and vary their compositions each as 1.00, 1.50, 2.00, 2.50
- To carry out isothermal treatment on the developed alloy samples using DTAT-T7, which involve solution treatment, pre-Ageing and Over-Ageing.
- To investigate the tensile strength and hardness properties of the various alloy samples
- To study the microstructural evolutions of the various alloy samples.

Literature Review

The concept of alloy has been explained in different ways by different scholars and authors, even though all are linked to the same meaning. Alloy is a mixture or metallic solid solution composed of two or more elements. In this context, an alloy is composed of an alloying element (the solute) and the matrix or the base metal (the solvent). Matula *et al.* (2008) [31], have explained the term alloy as a mixture of atoms in which the main or primary constituent is a metal, usually referred to as the matrix or the solvent. The secondary constituents are called the alloying elements or solutes and can be metal or non-metal. The main objective of alloying is to improve mechanical properties, which may result in the reduction of some other properties such as conductivity and corrosion resistance accompanying the process. The basic alloying elements for aluminium alloys are copper, silicon, magnesium, manganese, zinc and tin. There are two principal classifications of aluminium alloys, namely cast and wrought alloys, both of which are further subdivided into heat-treatable and non-heat-treatable. About 85% of aluminium alloy is used for wrought products, for example rolled plate, foils and extrusions. Cast aluminium alloys yield cost-effective products due to the low melting point, although they generally have lower tensile strength compared to wrought alloys. The most important cast aluminium alloy system is the Al-Si alloy, where the high levels of silicon (4.0–13%) contribute to give good casting characteristics (Vo, 2016) [45].

Aluminium-Silicon Alloy

Aluminium alloys consisting of the Al-Si are widely used in the automobile field, since they show excellent fluidity, castability, high-strength to density ratio, high wear resistance, good corrosion resistance, better low thermal expansion coefficient, heat treatability and improved mechanical properties in different temperatures or combination of these properties (Birol, 2009, Niranjani *et al.*, 2009; El-Sebaie *et al.*, 2008; Haghshenas *et al.*, 2008; Ovono *et al.*, 2006) [10, 34, 15, 20, 36]. Foundry Al-Si alloys comprise of about 85% to 90% of the total aluminium cast alloys, dominating the automotive application and market with about 75% in the form of castings (Hadley *et al.*, 2000) [19].

A356 is a general cast Al-Si alloy used in the automotive industries and aircraft, especially for casting of pistons, cylinder heads, cylinder blocks, and valve lifters owing to the above mentioned characteristics (Ashtari *et al.*, 2004; Wang *et al.*, 2003; Liao *et al.*, 2002 and Kilaas and Radmilovie, 2001) [5, 46, 26, 24]. Number of issues, in particular, weight reduction, fuel efficiency and enhanced mechanical performance in mechanical systems have stimulated research and development in order to develop alloys with high strength-to-density ratio to reduce vehicle weight (Heller *et al.*, 2010; Niranjani *et al.,* 2009; Zander and Sandstrom, 2008 and Madugu and Abdulwahab, 2006) [21, 34, 49, 28].

The solid solution strengthening is obtained in Al-Si alloys by adding Magnesium, which also provides the precipitation hardening (PH) in order to yield high strength (Feng *et al.*, 2009) [17]. Magnesium is the main solid solution strengthener to Al-Si alloy (to form Al-Si-Mg alloys) and its addition leads to increase in response to precipitation hardening which in turn results in higher yield strength in these alloys (Seyedrezai *et al.*, 2009) [41]. Al-6.5%Si-0.35%Mg alloy shows response to heat treatment (Haghshenans *et al.,* 2008) [20] and increase strength by precipitation of Mg_2Si in aluminum matrix (Zander and Sandstrom, 2008 and Evren and Bilgehan, 2007) [49, 16].

The field of adoption of such alloys is, however, strongly influenced by the component operating temperature. Mechanical properties of heat treatable cast Al-Si-Mg alloys (e.g. A356) are negatively affected by high temperature exposure ($T \geq 200^oC$) (Kasprazak *et al.*, 2014) [22].

Modification of Aluminium - Silicon Alloys

Alloying aluminium with silicon has not completely satisfied material engineers' quest to meet the functional requirements of Al-Si alloys, due to limitations of as-cast mechanical properties. Studies have shown that the microstructure of as cast Al-Si alloys under the conventional solidification conditions consists of coarse flakes of Si that promote brittleness within these alloys (Uzu *et al.*, 2001) [44]. Coarse columnar grain structures are developed by Al-Si cast alloys under normal casting conditions. But these structures can be transformed into fine grain structures and uniform distribution in the alloy by mechanical modification and through rapid cooling. Rapid cooling result in fine dendritic structures in the alloy (Zhang *et al.,* 2008 and Maube *et al.*, 2014) [50, 32]. Large dendritic structure is due to undercooling during solidification. Rate of cooling affects the size of critical nuclei, and subsequently, the effective number of nuclei that will ultimately produce fine-grained structures (Manente and Timelli, 2011) [29].

Consequently, materials engineers and scientists have developed several processes of enhancing Al-Si alloys mechanical and physical properties. The properties of a material are defined by the characteristics of its microstructure. In the case of Al-Si alloys, microstructures can be modified by either chemical, thermal or mechanical methods. In a chemical modification, certain elements are added in trace levels to the matrix depending the property required (Uzu *et al.,* 2001) [44]. Modification of the eutectic silicon phase in hypoeutectic Al-Si alloys is carried out extensively in industry to improve mechanical properties, particularly ductility. Modification results in a structural transformation of the silicon phase from a plate-like, to a fine fibrous morphology (Liu, *et al.*, 2015) [27].

Generally, modification and refinement processes are used for improving mechanical properties of alloys by altering the alloy's Si morphology and distribution. There are several modification and refinement techniques that can be used and these techniques can be categorized into three (Chang and Ko, 2000) [11]:

1. Chemical modification and refinement processes; addition of a calculated quantity of nucleation agents
2. Mechanical modification and refinement processes; ultrasonic, squeeze, stirring, centrifugal and vibration methods
3. Thermal modification process; superheating, quench and cooling

The addition of trace levels of certain additive (modifier) to a molten Al-Si in order to alter its structure is called modification. Modification reduces the size of eutectic Si particles to enhance its mechanical properties such as ductility and strength. Chemically stimulated modification produces a fine flake-like or fibrous structure. Many elements have been discovered to produce a fibrous eutectic Si structure such as Na, Sr, K, Cs and Ca. These following elements, Sb, As, and Se have been found to also produce a refined flake-like structure. These three elements Sr, Na, and Sb are the most effective modifiers in trace levels of additions and widely used in the foundry industry. The strongest modifiers known are Na and Sr. Other modifying elements are K, Rb, Ba, La, Yb, As and Cd, (Ebhota and Innambao, 2016 and Sukiman *et al.*, 2012) [13, 42].

Because the elements causing modification, including Na, Sr, Sb, Ba, Ca, Y, Yb and mischmetals (mixture of Lanthanum, Cerium, Praseodymium and Neodymium), all have an atomic radius ratio close to 1.65, the theory is generally well accepted. Among the rare earth elements, Eu and Yb have the most optimal ratios with $r = r_{Si}$ of 1.70 and 1.66, respectively, while other rare-earth elements have a ratio in the range of 1.48 (Lu) to 1.61 (La). Even though the impurity induced twinning theory is well accepted, there are still some questions and contradictions that remain (Chang, 2001 and Chang and Ko, 2000 [11]).

Heat Treatment of Aluminium Alloys

Heat-treatment is of paramount importance, since it is commonly used to alter the mechanical properties of cast aluminium alloys. Heat-treatment improves the strength of aluminium alloys through a process known as precipitation-hardening which occurs during the heating and cooling of an aluminium alloy and in which precipitates are formed in the aluminium 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 (Sani *et al.*, 2016) [40].

1. Solution Heat Treatment of Aluminium Alloy

According to Barresi *et al.* (2000) [8], solution heat treatment must be applied for a sufficient length of time to obtain a homogeneous supersaturated structure, followed by the application of quenching with the aim of maintaining the supersaturated structure at ambient temperature. In Al-Si-Cu-Mg alloys**,** Solution treatment fulfills three roles:

- Homogenization of as-cast structure.
- Dissolution of certain intermetallic phases such as Al_2Cu and Mg_2Si.
- Change of the morphology of eutectic silicon.

Mohamed *et al.*, (2013) [33], stated that the segregation of solute elements resulting from dendritic solidification may have an adverse effect on mechanical properties. The time required for homogenization is determined by the solution temperature and by the dendrite arm spacing. Hardening alloying elements such as Cu and Mg display significant solid solubility in heat-treatable aluminum alloys at the solidus temperature; this solubility decreases noticeably as the temperature decreases. The changes in the size and morphology of the silicon phase have a significant influence on the mechanical properties of the alloy. It has been proposed that the granulation or spheroidization process of silicon particles through heat treatment takes place in two stages:

- Fragmentation or dissolution of the eutectic silicon branches and
- Spheroidization of the separated branches.

During solution treatment, the particles undergo changes in size and in shape. In the initial stages, the unmodified silicon particles undergo necking and separate into segments, which retain their original morphology. As a result of the separation, the average particle size decreases and the fragmented segments are eventually spheroidized. The spheroidization and the coarsening of eutectic Si can occur concurrently during the second stage (Mohamed *et al.*, 2013) [33].

2. Precipitation Hardening Heat Treatment of Aluminium Alloy

Heat-treatment is commonly applied to change and improves the mechanical properties of aluminium alloys and this treatment is called precipitation hardening. Precipitation hardening is commonly used to process aluminium alloys and other non-ferrous metals for commercial application. The examples are aluminium-copper alloys, copperberyllium alloy, copper-tin alloy, magnesium-aluminium alloy and some other ferrous alloys. This treatment is known Precipitation hardening which includes the solution treating of the alloy above solvus temperature to allow solutionizing of the second phase followed by quenching in water to room temperature and finally it could be heated to a temperature above room temperature to allow precipitation (Frank, 2012) [18].

After appropriate heat treatment of precipitation hardening, the strength and hardness of some heat-treatable aluminium alloys can be enhanced by the formation of second-phase fine precipitated particles within the matrix. The fine precipitates in the alloy impede dislocation movement by forcing the dislocations to either cut through the precipitated particles or go around them. By restricting dislocation movement, the alloy is strengthened. The general requirements for precipitation strengthening include (Donaled *et al.*, 2010) [12]:

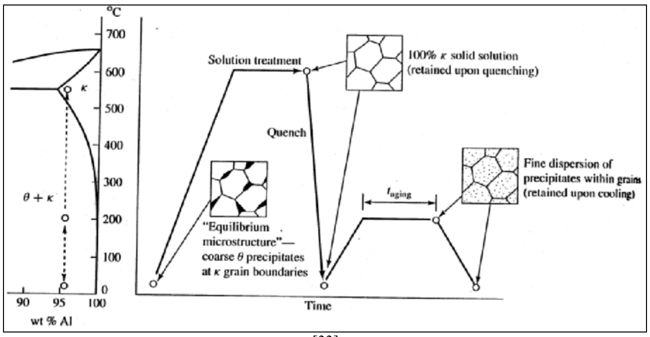
1. The alloying element should have significant solid solubility in aluminium and the solubility of alloying elements decreases with decreasing temperature.
2. The matrix should be relatively soft and ductile, and the precipitate should be hard and brittle. In most age hardenable alloys, the precipitate is a hard, brittle intermetallic compound.
3. The alloy must be quenchable, that is capable of formation of supersaturated solid solution (SSSS) after quenching.
4. Formation of uniform, finely precipitates during aging heat treatment (a coherent precipitate with matrix must be formed).

The precipitation hardening consists of three main steps (Toschi, 2018) [43]:

1. Solution heat treatment: To dissolve soluble phases
2. Quenching: to create a supersaturated solid solution
3. Age hardening: for precipitation of solute atoms either (natural ageing) or (artificial ageing).

3. Double Thermal Ageing Treatment (DTAT)

Sani *et al.* (2016) [40], stated that the double thermal ageing treatment (DTAT) is a form of multi-step thermal ageing treatment that includes ageing at low temperature and then followed by a high temperature ageing for a sufficient time above 150ºC for aluminium T6 temper conditions. There have been several researches that have reported on DTAT of aluminium alloy as a means for improving both the strength and SCC resistance of which Al-Zn-Mg-Cu (7075) is one of the most popular alloys. According to Wang *et al.* (2016) [47], DTAT-T7 is a temper treatment consisting of triple stage ageing (pre-ageing, quenching and ageing).



Source: Mohamed *et al.* (2013) [33].

Fig 1: Detailed Temperature-Time Diagram for Temper Treatment

Materials and Method

In this chapter the research design, which includes the coding systems for the various samples, the materials and the equipment to be used as well as the research methodology will be discussed.

Materials Required

The following are the materials that are required for the development of the A356.0 type (Al-7%Si-0.3%Mg) alloy samples and the modifier additions:

- Commercially pure aluminium (Al) metal
- Silicon (Si) metal
- Magnesium (Mg) metal
- Cerium (Ce) metal

Samples Development

The sample used Al-7%Si-0.3%Mg alloys was developed during the research. Cerium was added in the range of 0.50, 1.00, 1.50, 2.00 and 2.50 percent by mass.

Isothermal treatment was carried out on the samples after which, strength and hardness were investigated and microscopic evolutions studied.

Experimental Design

The followings are the samples designation for easy identification.

Table 1: Samples Coding

S. No	Sample Code	%Ce	Heat Treated	Non-Heat Treated
1	AS1	0	AS1H	AS1N
2	AS2	0.5	AS2H	AS2N
3	AS3	1.0	AS3H	AS3N
4	AS4	1.5	AS4H	AS4N
5	AS5	2.0	AS5H	AS5N
6	AS6	2.5	AS6H	AS6N

Table 1 shows the coding of the samples prepared for testing in the research. AS1 is the one with 0%Ce, that is pure Al-Si-Mg alloy, while AS2 is the sample with 0.5%Ce, AS3 has 1%Ce, AS4, 1.5%Ce, AS5, 2%Ce and AS6 contained 2.5%Ce. H is added last for heat treated samples, while N is added at te end of non-heat treated samples.

Casting of the Alloys

The procedure for the research started with sourcing for the materials for the development of the alloy specimens (samples). Charge calculation was carried out to know the quantity of each of the metals to be used and the various loses and gains to be incurred. After charge calculation melting and alloying were followed as well as mould preparation and then casting in two different shapes – cylindrical and block shapes.

Commercial A354 alloy will be produced in an appropriate furnace at 750ºC under Ar atmosphere according to Abdulwahab *et al.*, (2011) [1], Adeboye *et al.*, (2015) [3] and Anna *et al.,* (2018) [4]. The rare earth metals was added in the form of master alloy or pure metals and calculated form to refine and spherodized the eutectic Si. The melt was stirred thoroughly and poured in sand mould. From the cast ingot, block and cylindrical bars for experimental activities were obtained. The chemical composition of the cast A354 alloy was evaluated by Glow Discharge Optical Emission Spectroscopy and results reported in tabular form. The average value of the Secondary Dendrite Arm Spacing

(SDAS) and aspect ratio of eutectic silicon particles will be calculated through optical microscopy by image analyses.
The casted alloy samples were drawn into cylindrical shapes for tensile test. The block samples were shaped for hardness test and microscopic examination. Each of the specimens were prepared in two pieces, one as cast, and the other to be aged hardened (pre-ageing and over-ageing treatments-T7). Alloys in T7 tempers are over-aged, which means that some degree of strength has been sacrificed or "traded off" to improve one or more other characteristics.

Experimental Testing Techniques
The following were the tests carried out in the research:
Ultimate Analysis
The Ultimate analysis of the A356 (Al-Si-Mg) alloy casted before the addition of Ce show that the chemical composition is Al-7.065%Si-0.432%Mg-0.271%Fe-0.121%Ti-0.044%Mn-0.008%Cu-0.037%Zn-0.0003%Na.
The analysis was not done after the cerium modifier was added.

Tensile Test
This was carried out on a universal tensile testing machine on the as cast and heat treated specimen of various compositions. Tensile Specimen has enlarged ends or shoulders for gripping. The important part of the specimen is the gage section. The cross-sectional area of the gauge section is reduced relative to that of the remainder of the specimen so that deformation and failure will be localized in this region. Tensile tests were carried out with the use of universal testing machine (TQSM 1000), which had digital load and displacement meters attached for the measurement of applied tensile loads (kN) with corresponding specimen longitudinal displacements (mm).

Hardness Test
This was done using Brinell hardness testing machines and will be carried on as cast and heat treated specimens of various compositions. Brinell and Rockwell are among the hardness tests most commonly used in industry. The TQSM 1000 Universal Testing machine was used for the Brinell's hardness test, where a 10 mm diameter indenter was used. A digital load meter, attached to the machine, measured the load (kN) that created indentations on the specimens with 20s dwell time. While a microscope was used in measuring the diameter (mm) of indentations. The Brinell hardness number, HBN, was computed by fitting the values of the measured parameters into the Brinell's hardness formula. The value of the Brinell Hardness Number (BHN) is obtained by performing calculations using the following formula (ASTM E10):

$$BHN = \frac{2P}{\left|\pi D\left\{D - \sqrt{(D^2 - d^2)}\right\}\right|}$$

Where P = Load applied, D = Diameter of indenter, d = Diameter of indentation. The load used was 60kgf for a duration of 30 seconds (Krishna and Karthik, 2014) [25].

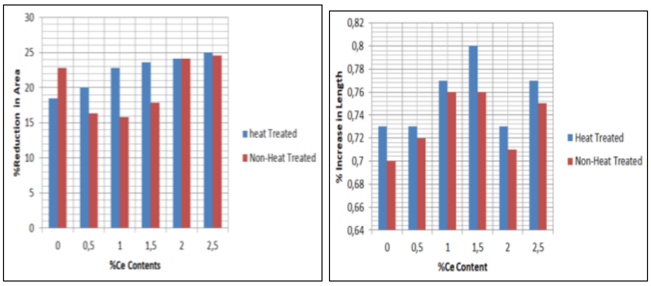
Microstructural Examination
Samples were grinded, polished and etched using Keller's reagent, then Scanning Electron Microscope (SEM) was used to reveal microstructural details. The microstructure homogeneity as well as the distribution of particles of crystallized secondary phases was estimated by SEM using JSM-6490LV (JEOL, Tokyo, Japan) at an accelerating voltage of 20kV. To study the microstructure, thin foils were used, produced by jet polishing on a Tenupol-5 machine (Struers, Ballerupcity, Denmark) with the chemical solution consisting of 20% nitric acid and 80% methanol at a temperature of - 25°C and a voltage of 15V. A mean size of structural elements was determined based on the measurements of at least 200 mean diameters.

Results and Discussions

Table 2: Geometric Parameters of Cerium modified Al-Si-Mg Alloy Tensile Specimens

Specimens	D_o (mm)	D_f (mm)	G_o (mm)	G_f (mm)	ΔA (mm)	ΔL (mm)	%ΔA (mm)	%ΔL (mms)
AS1H	5.40	4.00	26.10	24.20	1.00	1.90	18.52	0.73
AS2H	5.50	4.00	26.20	24.30	1.10	1.90	20.00	0.73
AS3H	5.70	4.40	26.00	24.00	1.30	2.00	22.81	0.77
AS4H	5.50	4.20	26.20	24.10	1.30	2.10	23.64	0.80
AS5H	5.80	4.40	26.10	24.20	1.40	1.90	24.14	0.73
AS6H	5.60	4.10	26.10	24.00	1.40	2,00	25.00	0.77
AS1N	5.70	4.40	26.00	24.18	1.30	1.82	22.81	0.70
AS2N	5.50	4.60	26.20	24.31	0.90	1.89	16.36	0.72
AS3N	5.70	4.80	26.10	24.11	0.90	1.99	15.79	0.76
AS4N	5.60	4.60	26.00	24.02	1.00	1.98	17.86	0.76
AS5N	5.40	4.10	26.10	24.25	1.30	1.85	24.10	0.71
AS6N	5.70	4.30	26.20	24.23	1.40	1.97	24.56	0.75

The Fig 2 above was used to develop the figures 2 and 3 below



(a) Percentage Reduction in Area (b) Percentage Increase in Length

Fig 2: Comparison of the Tensile Geometries of Heat Treated and Non-heat treated samples of the A356 Alloy

From figure 2 (a) it can be observed that for AS1, non-heat treated sample reduced more in diameter before rupture as compared to heat treated sample. In the case of AS2, AS3, AS4 and AS6, heat treated samples reduced more than the non-heat treated samples before breaking. The AS5 samples are almost of the same values. This means that heat treatment of the cerium modified A356 alloy is better achieved when the percentage of cerium added is 0.5; 1.0; 1.5 or 2.5. Sample without cerium perform better on tensile loading than heat treated sample.
Figure 2 (b) show that heat treated samples extended more in length before rupture compared to the non-heat treated samples. An indication that heat treatment of cerium modified A356 alloy will improve its ductility. The highest value of the percentage increase in length is that containing 1.5%Ce and heat treated.

Table 3: Tensile Properties of Ce Modified Al-Si-Mg Alloys Specimens

Specimen	U.T.S (MPa)	B.S (MPa)	P.S (MPa)	Ɛ
AS1H	410.78	410.78	0.07	0.04
AS2H	430.02	430.02	0.09	0.05
AS3H	432.37	432.37	0.12	0.06
AS4H	435.88	435.88	0.15	0.07
AS5H	443.17	443.17	0.19	0.08
AS6H	447.86	447.86	0.24	0.09
AS1N	400.50	400.50	0.06	0.03
AS2N	419.43	419.43	0.08	0.04
AS3N	425.38	425.38	0.10	0.05
AS4N	430.51	430.51	0.13	0.06
AS5N	438.38	438.38	0.16	0.07
AS6N	442.62	442.62	0.21	0.08

The Table 3, above, shows the tensile properties of the samples of the cerium modified aluminium silicon alloy, heat treated and non-heat treated. The table was used to develop the figures 4 and 5 below.

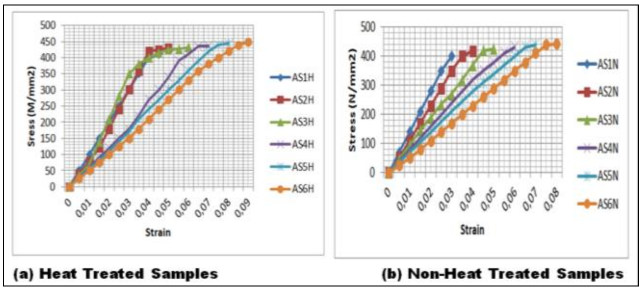


Fig 3: Stress-Strain Curves of various Samples Tested

In figure 3, (a) is the set of curves for heat treated cerium modified A356 alloy, while (b) are the non-heat treated samples. It can be observed that in both (a) and (b), sample with 2.5%Ce extended highest compared to others and also in both cases the alloy sample without Ce had the least extension. This is an indication that addition of the cerium had improved the ductility of the alloy samples. That means that the purpose of the addition of the cerium based on mechanical properties was achieved.

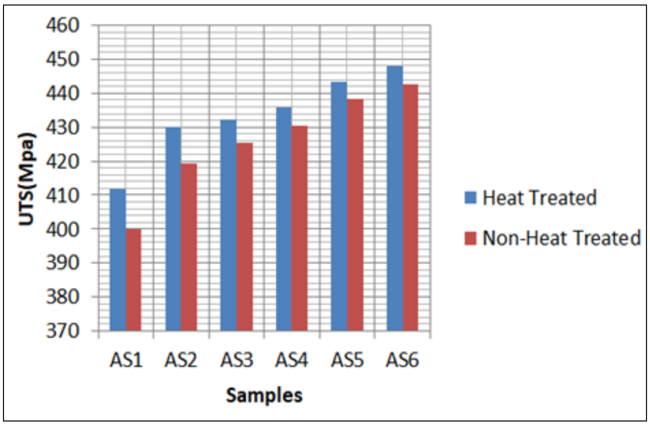


Fig 4: Comparative Bar Chart of the Heat Treated and Non-Heat Treated A356 Ce Modified Samples

Fig 4 gives the comparison among the heat treated and the non-heat treated alloy samples of the A356 alloy modified by cerium. For all the samples, heat treated samples are better than the non-heat treated samples. The least samples are for the AS1, where the heat treated sample failed at UTS of 411.78MPa after total strain of 0.045 and the non-heat treated sample failed at 400.05MPa after strain of 0.030. As for the samples with the highest values of UTS, heat treated samples failed at 447.86MPa with strain of 0.090, while the non-heat treated sample failed at 442.62MPa with strain value of 0.080.

These display the dominance of the impact of heat treatment on the samples over non-heat treatment and informed the implication of heat treatment on the ductility of cerium modified A356 alloy.

Table 4: Indentation, d (mm) and Brinell hardness number (HBN) of various Alloy Specimens

Specimens	%Ce Contents	Indentation, d (mm)	HBN(N/mm^2)
AS1H	0	0.43	307
AS2H	0.5	0.38	374
AS3H	1.0	0.35	390
AS4H	1.5	0.36	410
AS5H	2.0	0.35	421
AS6H	2.5	0.39	439
AS1N	0	0.40	349
AS2N	0.5	0.37	371
AS3N	1.0	0.40	391
AS4N	1.5	0.41	423
AS5N	2.0	0.40	446
AS6N	2.5	0.38	459

Table 4 shows the values of hardness for all the specimens under study. It is revealed that the more the cerium content, the more is the HBN value. For instance, the value for HBN are 307, 390 and 439 for AS1H (0%Ce), AS3H (1.5%Ce), AS6H (2.5%Ce) heat treated specimens respectively, while the corresponding non-heat treated samples have 349, 391 and 459 for AS1N (0), AS3N (1.5) and AS6N (2.5) respectively.

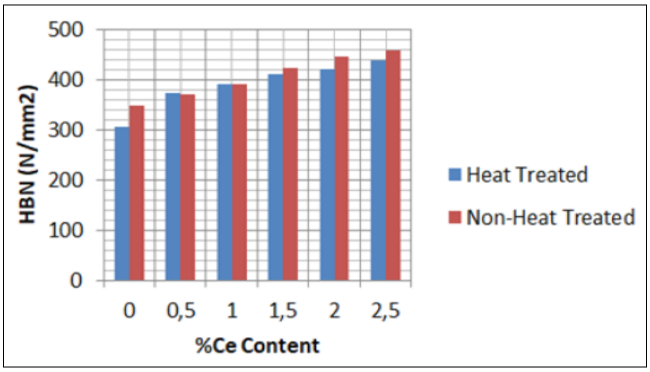


Fig 5: Comparative Bar Chart of the HBN of the various Ce Modified A356 Samples

Figure 5n present the pictorial view of the specimens used for the research. As can be seen specimens with the least HBN are specimens with 0%Ce contents. The non-heat treated sample has higher HBN value than the heat treated one, this is due to the fact that heat treatment induced ductility to the heat treated sample as such indentation is easier.

Samples with percentage cerium contents of 0.5 and 1.0 are almost of the same height while for the samples with 1.5, 2.0, and 2.5 the non-heat treated samples have higher HBN as depicted by the height of their bars.

Microstructures

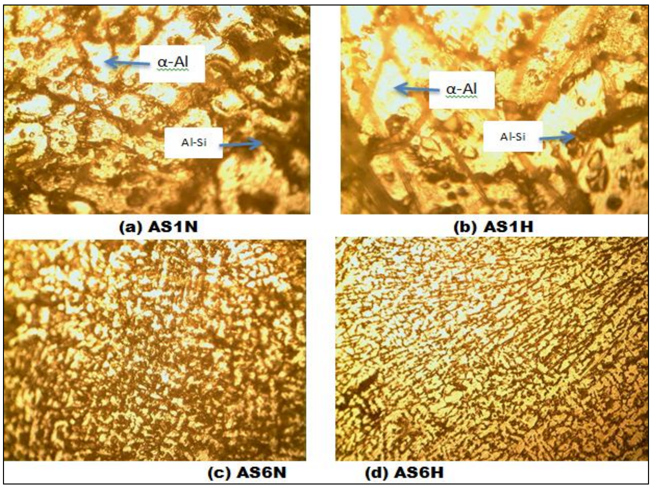


Plate 1: Microstructures of some of the A356 alloy samples

Plate 1 shows the microstructures of the least and highest performing samples of the A356 alloy used for the research for heat treated and non-heat treated samples. As for (a) and (b), for the A356 with 0%Ce contents, it can be observed that there are segregations of alpha aluminium (α-Al) and Al-Si eutectic structures scattered on the matrix. The conditions are more predominant in the sample (a), which was not heat treated than in the heat treated sample, owing to the fact that most of the structures might have been dissolved by the heat treatment.

Plate 1(c) and (d) are for 2.5% cerium contents specimens, where (c) is non-heat treated and (d) is heat treated samples. Sample (c) has all the structures (α-Al and Eutectic silicon) modified into finer structure, but the heat treated samples are finer and evenly distributed than the non-heat treated one.

Conclusions

The research results shows that addition of cerium to aluminium silicon magnesium (A356) alloy improved their strength and ductility due to the modification of brittleness induced structure of silicon called eutectic silicon. The result shows that the more the cerium added the better is the modification. It also revealed the importance of heat treatment in modification of aluminium silicon alloys. This is seen in the comparison of the various samples as: AS1 (18.50 vs 22.81); AS2 (20.00 vs 16.36); AS3 (22.81 vs 15.79); AS4 (23.64 vs 17.86); AS5 (24.14 vs 24.10); AS6 (25.00 vs 24.56) for percentage reduction in area after tensile testing.

Acknowledgements

We sincerely appreciate the management of Abdullahi Fodio University of Science and Technology, Aliero, Kebbi State and Tertiary Education Trust Fund (TETFund) of the Federal Republic of Nigeria for their financial support for the success of the research.

References

1. Abdulwahab M, Madugu IA, Yaro SA, Hassan SB, Popoola API. Effects of Multiple-Step Thermal Ageing Treatment on the Hardness Characteristics of A356.0-type Al-Si-Mg Alloy. Materials and Design. 2011; 32(3):1159.
2. Abdulwahab M, Popoola API, Kikawa CR. Statistical evaluation of hardness behavior in a thermally aged A356.0-type Al-Si-Mg alloy. International Journal of Physical Sciences, September 23, 2012; 7(36):5391-5406. Available online at: http://www.academicjournals.org/IJPS Doi: 10.5897/IJPS12.371. ISSN: 1992-1950 ©2012 Academic Journals
3. Adeboye GO, Abdulwahab M, Asuke F, Yaro SA. Effect of Pre-Ageing Thermal Conditions on the Corrosion Properties of Antimony-Modified Al-Si-Mg Alloy. Nigerian Journal of Technology (NIJOTECH), October 2015; 34(4):705-709. Copyright© Faculty of Engineering, University of Nigeria, Nsukka, ISSN: 0331-8443. www.nijotech.com. Doi: http://dx.doi.org/10.4314/njt.v34i4.6
4. Anna Zykova, Lyudmila Kazantseva, Natalya Popova, Alexander Vorozhtsov, Irina Kurzina. Influence of Modifying Mixtures on Si Crystal Formation in Al-7%Si Alloy. Metals. 2018; 8:98. Doi: http://doi.org/10.3390/met8020098. www.mdpi.com/journal/metals
5. Ashtari P, Tezuka H, Sato T. Influence of Li addition on intermetallic compound morphologies in Al-Si-Cu-Fe cast alloys, Scripta Materialia. 2004; 51(1):43-46.
6. Asuke F, Aigbodion VS, Abdulwahab M, Fayomi OSI, Nwoyi CI, Garba B. Effects of bone particle on the properties and microstructure of polypropylene/bone ash particulate composites. Results in Physics. 2012; 2(28):135-141.
7. Ayeni FA, Madugu IA, Sukop P, Ihom AP, Alabi OO, Okara R, *et al*. Effect of Aqueous Extracts of Bitter Leaf Powder on the Corrosion Inhibition of Al-Si Alloy in 0.5 M Caustic Soda Solution. Journal of Minerals and Materials Characterization and Engineering. 2012; 11:667-670. Published Online July 2012. http://www.SciRP.org/journal/jmmce.
8. Barresi J, Kerr MJ, Wang H, Couper MJ. Effect of Magnesium, Iron, and Cooling Rate on Mechanical Properties of Al-7Si-Mg Foundry Alloys, AFS Transactions, 2000, 563-570.
9. Barrirero J, Pauly C, Engstler M, Ghanbaja J, Ghafoor N, Li J, *et al*. Eutectic modification by ternary compound cluster formation in Al-Si alloys, 2019. Received: 15 January 2019; Accepted: 19 March 2019. Published Online: 02 April, 2019.
10. Birol Y. Response to artificial ageing of dentritic and globular Al-7%Si-Mg alloys. Journal of Alloy Compound. 2009; 484:164-167.
11. Chang JY, Ko HS. Twin probability of eutectic si in rare earth modified Al-7wt%Si alloy. Journal of Materials Science Letters. 2000; 19:197-199.
12. Donaled R, Askeland Pradeep P, Fulay, Wendelin I, Wrigin. The Science and Engineering of Materials. Sixth Edition. Cengage Learning, Inc, 2010.
13. Ebhota WS, Inambao FL. Principles and baseline knowledge of functionally graded aluminium matrix materials (FGAMMs): Fabrication techniques and applications. International Journal of Engineering Research in Africa. 2016; 26:47-67.
14. Eda Dağdelen, Ali Ulus. Aluminum Sheet Production: Heat Treatment of Aluminium and Temper Designations of Aluminium Alloys. Teknik Alüminyum A.Ş. - Türkiye, 2015.

15. El-Sebaie O, Samuel AM, Samuel FH, Doty HW. The effects of mischmetal cooling rate and heat treatment on the eutectic Si particle Characteristics of A319.1, A356.2 and A413.1Al-Si casting alloys, Mater Sci Eng A480. 2008; 342.
16. Evren Tan, Bilgehan Ogel. Influence of heat treatment on the mechanical properties of AA6066 alloy. Turkish Journal of Engineering and Environmental Science. 2007; 31:53-60.
17. Feng Wang, Jishon Zhang, Baiqing Xiong, Yongan Zhong. Effect of Iron (Fe) and Manganese (Mn) Addition on Microstructure And Mechanical Properties of Spray-Deposited Al-20Si-3Cu-1Mg Alloy. Journal of Material Character. 2009; 60:384-388s.
18. Frank C. Heat Treatment-Conventional and Novel Application. Croatia, 2012, 229-234.
19. Hadley SW, Das S, Miller JW. Aluminum Research and Development (R&D) for Automotive uses and the Department of Energy's Role. R&D Report/Findings for the Energy Division, Office of Advanced Automotive Technologies US (ORNLTM -1999/152), 2000, 1-7.
20. Haghshenans M, Zarei-Hamzaki A, Fatemi-Varzaneh SM. Effect of Thermo Mechanical Properties on the Microsructure of Thioxocast A356 Aluminium Alloy. Journal of Material Science and Engineering. 2008; 480:68-74.
21. Heller DK, William G, Fahrenholtz M, Keefe JO. The effect of post-treatment time and temperature on cerium-based Conversion coatings on Al 2024-T3, Corrosion Science. 2010; 52:360.
22. Kasprazak W, Amirkhiz BS, Niewczas M. Structure and properties of cast Al-Si based alloy with Zr-V-Ti additions and its evaluation of high temperature performance. Journal of Alloys Compound. 2014; 595:67-79.
23. Khalel Ahmed Ragab, Mohamed Bouazara, Xiao Grant Chen. Influence of Thermal Ageing Parameters on the Characteristics of Aluminum Semi-Solid Alloys. Metals. 2018; 8:746. Received: 10 September 2018; Accepted: 20 September 2018; Published: 23 September 2018. Doi: http://doi.org/10.3390/met8100746. www.mdpi.com/journal/metals
24. Kilaas R, Radmilovic V. Structure determination and structure refinement of Al2CuMg precipitates by quantitative high-resolution electron microscopy, Ultramicroscopy. 2001; 88(1):63-72.
25. Krishna R, Karthik M. Evaluation of Hardness Strength of Aluminium Alloy (AA6061) Reinforced with Silicon Carbide. International Journal on Recent Technologies in Mechanical and Electrical Engineering (IJRMEE). 2014; 1(4):14-18. ISSN: 2349-7947
26. Liao H, Sun Y, Sun G. Correlation between mechanical properties and amount of dendritic α-Al phase in as-cast near-eutectic Al-11.6% Si alloys modified with strontium. Materials Science and Engineering A. 2002; 335(1-2):62-66.
27. Liu X, Zhang Y, Beausir B, Liu F, Esling C, Yu F, *et al*. Twin controlled growth of eutectic Si in unmodified and Sr-modified Al-12.7%Si alloys investigated by SEM/EBSD, Acta Mater. 2015; 97:338-347. Doi: http://doi.org/101016/j.actamat.2015.06.041
28. Madugu IA, Abdulwahab M. The effect of Cr addition on the mechanical properties of Al-Si-Fe alloy. Journal of Researc in Engineering. 2006; 3(4):29-33.
29. Manente A, Timelli G. Optimizing the Heat Treatment Process of Cast Aluminium Alloys, Recent Trends in Processing and Degradation of Aluminium Alloys. Rijeka, Croatia: InTech, 2011, p. 9.
30. Mario De Giovanni, James A Kaduk, Prakash Srirangam. Modification of Al-Si Alloys by Ce or Ce with Sr. Aluminum: New Alloys and Heat Treatment. JOM. 2019; 71(1). Doi: https://doi.org/10.1007/s11837-018-3192-6
31. Matula G, Jardiel T, Jimenez R, Levenfeld B, Várez A. Microstructure, mechanical and electrical properties of Ni-YSZ anode supported solid oxide fuel cells. Scientific Journal published monthly by the World Academy of Materials and Manufacturing Engineering. Archives of Materials Science and Engineering, 2008, 21-25. Doi: https://doi.org/10.1007/BF02755923
32. Maube SE, Wang'ombe DN, Maranga SM, Kihiu JM. Effect of cooling rate and heat treatment on the microstructure and impact resistance of recycled aluminium sand cast alloy. Journal of Sustainable Research in Engineering. 2014; 1:24-30.
33. Mohamed A, Samuel FH, Kahtani SAl. Microstructure, tensile properties and fracture behavior of high temperature Al-Si-Mg-Cu cast alloys. Mater. Sci. Eng. A. 2013; 577:64-72.
34. Niranjani VL, Hari Kumar KC, Subramanya SV. Development of high strengthAl-Mg-Si AA6061 alloy through cold rolling and ageing, Mater SciEng A515. 2009; 169.
35. Nnanna LA, Obasi VO, Nwadiuku OC, *et al*. Archives of Applied Science Research. 2012; 4:207-217.
36. Ovono OD, Guillot I, Massinon D. The microstructure and precipitation kinetics of a cast aluminium alloy. Scripta Mater. 2006; 55:259-262.
37. Popoola API, Fayomi OSI, Abdulwahab M. Degradation behaviour of Aluminium in 2M HCl/HNO3 in the presesnce of Archis hypogeae Natural Oil. International Journal of Electrochemical Science. 2012; 7:5817-5827.
38. Samuel AM, Elgallad EM, Doty HW, Valtierra S, Samuel FH. Effect of metallurgical parameters on the microstructure, hardness impact properties, and fractography of Al-(6.5-11.5) wt% Si based alloys, Mater. Des. 2016; 107:426-439. Doi: http://doi.org/10.1016/j.matdes.2016.06.051
39. Samuel GH, Garza-Elizondo AM, Doty HW, Samuel FH. Role of modification and melt thermal treatment processes on the microstructure and tensile properties of Al-Si alloys, Mater. Des. 2015; 80:99-108. Doi: http://doi.org/10.1016/j.matdes.2015.05.013
40. Sani LM, Abdulwahab M, Yaro SA, Kolawole FO. Inhibitive Effect by Psidium Guajava Leaf Extract on the Corrosion of Double Thermally-Aged Al-Si-Mg (SSM-HPDC) Alloy in Simulated Seawater Environment. Portugaliae Electrochimical Acta. 2016; 34(2):119-129. Doi: http://doi.org/10.4152/pea.201602119
41. Seyedrezai Hossein, Grebennikov Dmitrij, Mascher Peter, Zurob Hatem S. Study of the early stages of clustering in Al-Mg-Si alloys using the electrical resistivity measurements. Materials Science and Engineering A. 2009; 525:186-191.
42. Sukiman NL, Zhou X, Birbilis N, Hughes AE. Mol

JMC, Garcia SJ, *et al*. Durability and corrosion of aluminium and its alloys: Overview, property space, techniques and developments. In Ahmad, Z., editor. Aluminium Alloys-New Trends in Fabrication and Applications. ed Rijeka: In Tech, 2012, p. 2.

43. Toschi S. Optimization of A354 Al-Si-Cu-Mg Alloy Heat Treatment: Effect on Microstructure, Hardness, and Tensile Properties of Peak Aged and Overaged Alloy. Metals. 2018; 8:961. Doi: http://doi.org/10.3390/met8110961. www.mdpi.com/journal/metals
44. Uzu O, Karaaslan T, Keskin M. Production and structure of rapidly solidified Al-Si alloys. Turkish Journal Physics. 2001; 25:455-466.
45. Vo Nhon. Role of silicon in the precipitation kinetics of dilute Al-Sc-Er-Zr alloys. Materials Science and Engineering: A. 2016; 677(20):485. Doi: https//doi.org/10.1016/j.msea.2016.09.065
46. Wang G, Bain X, Wang W, Zhang J. Influence of Cu and Minor Elements on Solution Treatment of Al-Si-Mg-Cu Cast Alloys, Materials Letters. 2003; 57:4083-4087.
47. Wang K, Jiang HY, Jia YW, Zhou H, Wang QD, Ye B, *et al*, Nanoparticle-inhibited growth of primary aluminium in Al-10Si alloys. Acta Mater. 2016; 103:252-263.
48. Williams S Ebhota, Tien-Chien Jen. Effects of Modification Techniques on Mechanical Properties of Al-Si Cast Alloys. Aluminium Alloys - Recent Trends in Processing, Characterization, Mechanical behavior and Applications, 2017. © 2017 The Author(s). Licensee InTech. This chapter is distributed under the terms of the Creative Commons 2016 The Author(s). Licensee InTech. This chapter is distributed under the terms of the Creative Commons. Attribution License (http://creativecommons.org/licenses/by/3.0), which permits unrestricted. Doi: http://dx.doi.org/10.5772/intechopen.70391
49. Zander Johan, Sandstrom Rolf. One parameter model for strength properties of hardenable aluminium alloys. Materials Design. 2008; 28:1540-1548.
50. Zhang LY, Jiang YH, Ma Z, Shan SF, Jia YZ, Fan CZ, *et al*. Effect of cooling rate on solidified microstructure and mechanical properties of aluminium-A356 alloy. Journal of Materials Processing Technology. 2008; 207:107-111.