Journal of Engineering Innovations and Applications
Volume 2(1), pages 1-5, April 2023
Article Number: 31A2A88D1
ISSN: 2971-673X
https://doi.org/10.31248/JEIA2023.024
https://integrityresjournals.org/journal/JEIA

Full Length Research

Effect of chemical composition and T6 heat treatment on microstructure and mechanical properties of a hyper eutectic Al–Si alloy

Mangai M. M.[1]*, Aje Tokan[2], Mohammed Bawa[2] and Nicodemus Datau[1]

[1]Department of Mechanical Engineering, University of Jos, Jos, Nigeria.
[2]Department of Mechanical Engineering, Abubakar Tafawa Balewa University Bauchi, Bauchi, Nigeria.

*Corresponding author. Email: morganmangai32@gmail.com

Received 12th March 2023; Accepted 12th April 2023

ABSTRACT: The automotive and aircraft industries' requirements have led to increasing application of Al–Si alloys thanks to their great potential as a replacement to cast iron and steel. The current work is an investigation of the effect of chemical composition and T6 heat treatment on the microstructure and mechanical properties of a hyper eutectic Al–Si alloy. Secondary Al–Si alloy ingot was cast using the sand casting technique. Samples were prepared for microstructural examination and mechanical properties tests. One set of the samples was subjected to solution heat treatment at 530°C, quenched in water at room temperature and aged at 175°C for five hours. Microstructural examination of cast samples using scanning electron microscopy (SEM) revealed three main phases in the alloy. Primary α–Al dendritic phase, eutectic Si phase and intermetallic phases of Fe and Mg. After heat treatment, the eutectic Si phase was spheroidized and uniformly distributed, the bonding strength of the α–Al dendritic phase and Si eutectic phase were well distributed, and the Fe and Mg phases precipitated. The ultimate tensile strength and hardness improved by 37.17% and 40.38% respectively. T6 heat treatment is therefore a necessary step in the production of parts made of Al–Si alloy by sand casting.

Keywords: Aluminium–Silicon alloy, elemental composition, solution heat treatment, microstructural examination, hardness, ultimate tensile strength.

INTRODUCTION

To meet various requirements aluminium is alloyed with manganese, magnesium, zinc, nickels and silicon as major alloying elements. These alloying elements improve the physical and mechanical properties of aluminium. The alloys have a wide range of applications due to the unique combination of good corrosion resistance, lightweight, ease of fabrication, good mechanical properties and acceptable cost of aluminium. Its low density (2.7 g/cm^3) makes it the lightest metal other than magnesium (1.74 g/m^3) and beryllium (1.85 g/cm^3) (Mangai *et al*., 2019). But aluminium and its alloys are more versatile with fewer problems and less cost than magnesium and beryllium.

There are two principal classifications of aluminium alloys; casting alloys and wrought alloys. Both of these are further classified into two categories, heat treatable and non-heat treatable. Cast aluminium alloys yield cost effective products due to low melting point, although they generally have lower tensile strength than wrought products (Rajan *et al*., 2011). The most important cast alloy system is the aluminium-silicon alloy, where high levels of silicon (3-25%) contribute to good casting characteristics. The addition of silicon to aluminium makes it less viscous when in liquid form which together with low cost makes it a good casting alloy (Pezda, 2008). The aluminium-silicon alloys are well known casting alloys with higher wear resistance, low thermal expansion coefficient, good corrosion resistance and improved mechanical properties in a wide range of temperatures. These properties lead to the application of Al-Si alloys in the automotive industry especially for cylinder blocks, cylinder heads or pistons (Tillova *et al*., 2013).

Si additions to Al in the absence of other elements produce elemental Si particles and an Al–rich solid solution phase. In commercial alloys, it is quite common to have small amounts of Fe present as an impurity in the refining and smelting processes. At low Fe impurity contents, most of the Fe remains in a solid solution until eutectic reaction occurs yielding a solid solution of α–Al and Al3Fe intermediate (also called intermetallic) particles with a monoclinic crystal structure. The maximum solubility of Fe is 0.05% which is lower in commercial alloys. Commercial Al–Si alloys containing Fe impurities may form two types of intermetallic phases by a eutectic reaction. For alloys with low Si content, the Fe is present as Al3Fe while at higher Si levels, first α–Al12Fe3Si and at still higher Si levels β–Al9Fe2Si (Vander Voort and Asensio-Lozano, 2015).

According to Murray and McAlister (1984), the melting point of Al and Si are 660.45°C and 1414°C, while eutectic reaction occurs at 12.6 wt% Si and 557$\pm$1°C. Si solubility in Al is very low. The maximum solubility of Si in Al occurs at the eutectic temperature and is 1.65 wt%.

Nowadays, the usage of recycled (secondary) aluminium over primary aluminium is more beneficial as the production of primary aluminium consumes about 45 kwh/kg of metal while 2.5 kwh/kg of metal for secondary (recycled) aluminium alloys (Hurtalova *et al*., 2012). As a result of the increasing utilization of the secondary aluminium cast alloy, the necessity for strict control of mechanical properties and microstructure in order to minimize the delirious effect of impurities.

The microstructure and mechanical properties of the cast aluminium alloys can be improved upon by heat treatment. Heat treatment is an important operation in the final fabrication of many engineering components. The object of heat treatment is to make the metal better suited structurally and physically for some specific application (Rajan *et al*., 2011).

In Al-Si cast alloys, heat treatment is generally carried out to obtain an optimum combination of strength and ductility. The steps for the heat treatment consist of solution treatment, quenching and artificial ageing. The age hardening mechanisms responsible for strengthening are based on the formation of intermetallic compounds during the decomposition of a metastable supersaturated solid solution obtained by solution heat treatment and quenching (precipitation hardening). The mechanical properties of these alloys are significantly influenced by the presence of intermetallic phases and precipitates (Ibrahim *et al*., 2011; Michna and Naprstkova, 2012).

Tillova *et al*. (2013) undertook a scanning electron microscopy identification of intermetallic phases in Al-Si cast alloys. They noted that the mechanical properties and microstructure of Al–Si alloys are dependent on the composition, melt treatment conditions, solidification rate, casting process and the applied thermal treatment. They further stated that the mechanical properties depend besides the morphologies type and distribution of Si, Cu, Mg and Fe-phases on the grain size porosity distribution or profile.

Singh *et al*. (2016) studied the microstructure and mechanical properties of LM 25 alloy under the as-cast and T6 heat treatment conditions produced by the liquid metallurgy route. The outcomes showed that primary α - Al dendrites, eutectic silicon and MgSi are the main phases in the microstructure of LM25 alloy produced by the liquid metallurgy route. The hardness, ultimate tensile strength, yield strength and elongation of the LM25 alloy under T6 heat treatment improved by 14.8, 49, 73 and 18% respectively as compared to the as-cast condition.

Ramadan (2015) studied the influence of cyclic semi-solid heat treatment on the microstructure of Al-8% Si alloy containing 0.8% Fe. The specimens were heated in an electrically heated resistance furnace with a heating rate of 10°C min^{-1} to 585°C. For a complete one cycle heat treatment (5 minutes heating time), samples after 5 minutes of moulding at 585°C were cooled to a temperature of 550°C in still air cooling and the samples were taken out immediately for water quenching. It was found that heat treatment cycles should be limited to 3 cycles or less in order to maintain fine grain size and globular structure without agglomeration and coalescence. Cyclic semi-solid heat treatment changed the morphology of iron-rich intermetallic phases to be plate-like and fine plate iron-rich intermetallic phases instead of needle-like iron-rich intermetallic phases observed in as-cast samples.

Li *et al*. (2019) studied the effect of heat treatment (solution treatment and artificial ageing) on the microstructure and properties of as-cast Al 5Si1 Cu 0.5Mg aluminium alloy and composite reinforced with 1.5 wt% SiC particles. Results showed that the optimal solution time for the aluminium alloy and its composite was 9 and 6 hours respectively. The microstructure after solution treatment of the two materials consisted of a uniform distribution of nearby spherical eutectic Si and skeletal γ -phase. After artificial ageing at 175°C for 6 hours, the microstructure of the composite was more dispersed than the alloy and Al_2Cu was precipitated.

This work is aimed at investigating the effect of chemical composition and T6 heat treatment on the mechanical properties and microstructure of a cast hypereutectic Al-Si alloy.

MATERIALS AND METHODS

The base alloy used for the experiment was a secondary Al-Si alloy (prepared by recycling of aluminium scrap). The alloy melt was prepared from 10.5 kg ingots. The aluminium ingots were charged into a charcoal fired

Table 1 Chemical Composition of Aluminum – Silicon alloy.

Element	Na	Mg	Si	P	S	Cl	K	Ca	Ti	Cr	Mn	Fe	Zn	Al
%	0.98	0.97	18.79	0.02	0.02	0.49	0.03	0.14	0.05	0.02	014	1.36	0.78	rest

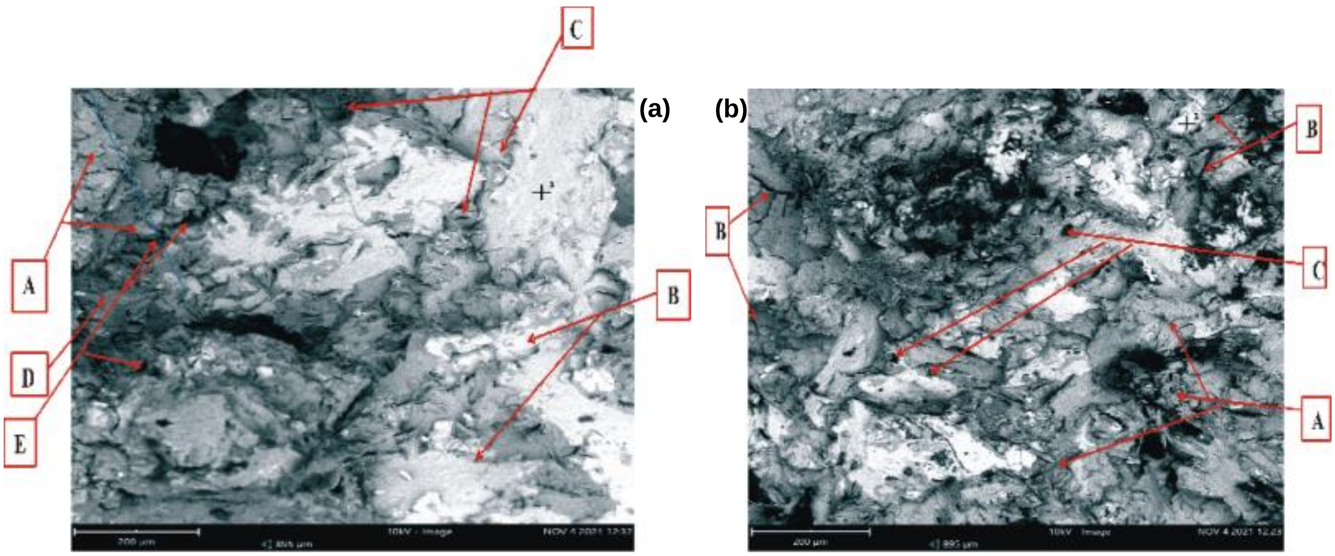

Figure 1. (a) SEM micrograph of as – cast sample, **(b)** SEM micrograph heat treated sample.

crucible furnace and heated to a temperature of 750 ± 30°C (above the liquidus temperature of the alloy) which is the casting temperature of aluminium. At this temperature, the slag was scoped and removed from the surface of the molten alloy. The molten alloy was then cast into prepared sand molds and allowed to cool. The chemical analysis of the alloy was carried out using optimum emission spectrometric analyzer (OES) as performed by Alaneme and Sanusi (2015). The results of the chemical composition are shown in Table 1.

Samples were then prepared for tensile strength and hardness tests. The prepared samples were subjected to T6 heat treatment conditions. This involved solution heat treatment at 530°C for one hour to form a solid solution then quenched in water at room temperature and aged at 175°C for 5 hours as performed by Bhat *et al*. (2014). This was performed using an electric resistance furnace model 5 – X-Y2.

To study the microstructure, test samples were cut from the castings. They were belt grinded and polished with abrasive paper of 200, 400, 600, 800 and 1000 grades respectively. They were then polished with emery cloth, washed and dried after which they were etched with Keller's reagent 3 (95 ml water, 2.5 ml HNO_3, 1.5HCl, 1.0 ml HF) by swabbing 10-20s before the microstructural examination. A scanning electron microscope (SEM) equipment equipped with energy dispersive spectroscopy (EDS) was used to study the microstructure of the alloy.

RESULTS AND DISCUSSIONS

Chemical composition

The result of the chemical analysis of the Al-Si alloy is presented in Table 1. Al is 76.42% while Si is 18.79%.

Microstructural examination of cast and heat treated alloy

Figure 1 shows the SEM micrograph of the cast and heat treated Al–Si alloy material. From the SEM micrograph of the as–cast sample in Figure 1(a), the alloy consists of a primary α–Al dendritic phase, Si-rich eutectic phase and intermetallic complex compounds of Fe and Mg. The white phase is suggested to be an insoluble Si-rich hard phase (Si is 18.79wt%) forming an irregular white phase (B) and needle like eutectic Al–Si precipitate (A). The primary α-Al phase showed a dendritic structure that is skeletal like particles (C) while the complex intermetallic hard phase of Fe and Mg is shown in the darker particles (Tillova *et al*., 2013). Si content beyond 12.6 wt.% is shown as the dark needle like particles along the interdendritic region, these particles precipitate out of the solid solution during the solidification process. These are known as primary Si not uniformly distributed and eutectic Al–Si (eutectic α - Al phase + eutectic Si phase) dark particles (E) as noted by Ramadan (2015). The combination of these phases makes

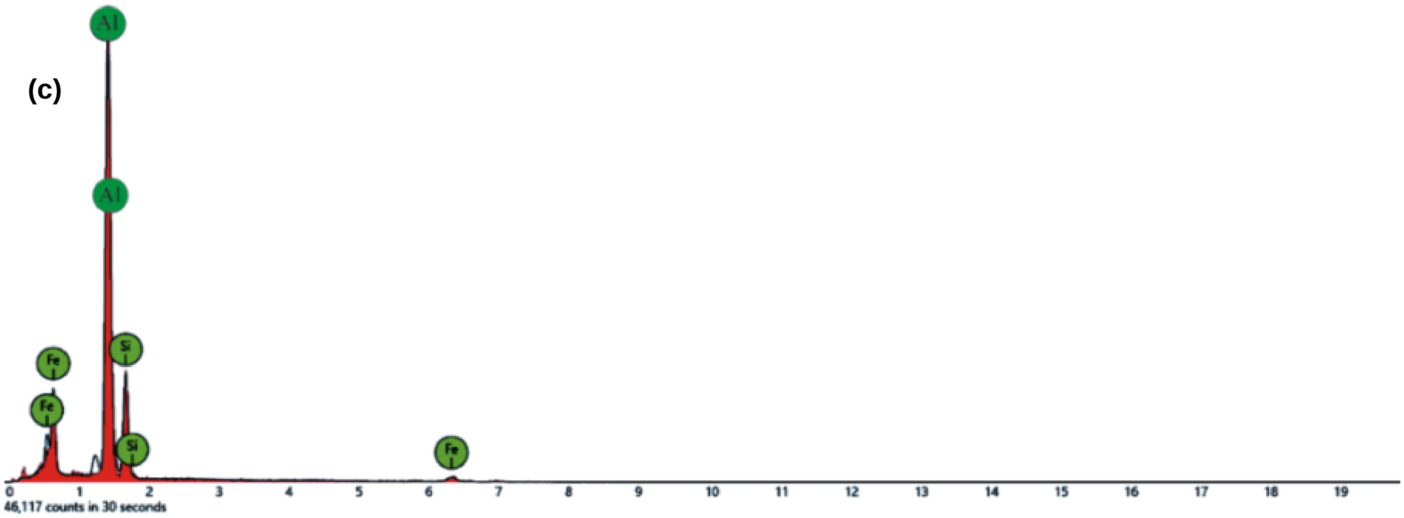

Figure 1c. EDS profile.

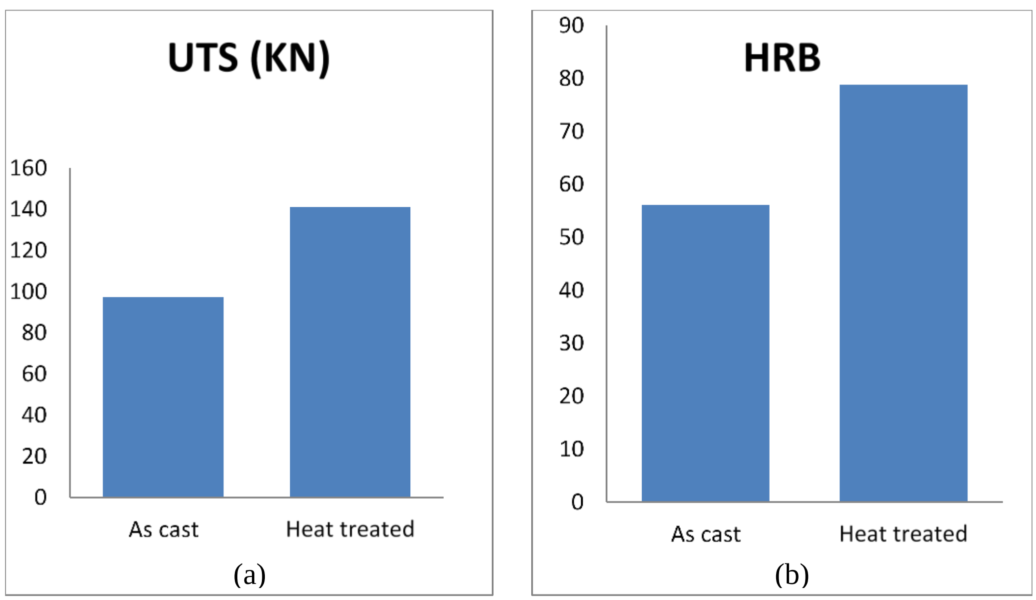

Figure 2. (a) Ultimate tensile strength (UTS) of sample, and **(b)** Brinell hardness (HRB) of sample.

the alloy hard. The Mg intermetallic phase forms a complex compound such as MgSi while Fe forms $Al_{15}(FeMg)_3Si_2$ and Al_5FeSi which are needle like hard brittle phases (D). These hard phases contribute to the micro-cracking and severe stress concentration in the as-cast material. The eutectic reaction occurs at 12.6wt%Si and 577±1°C. The maximum solubility of Si in Al at the eutectic temperature is 1.65 wt% (Vander Voort and Asensio-Lozano, 2009).

After heat treatment, the primary α–Al and eutectic Si phases decompose into spheroidized precipitate (C) (Figure 1(b)) and are distributed homogenously in the grain boundary. The dendrite structure breaks down into a denser phase due to dissolved Si precipitates (A). This in turn improves the mechanical properties of the alloy. From the micrograph, the primary Si phase dissolves causing a slip band (dislocation movement) (B). These slip bands are along the grain boundary. Quenching during T6 heat treatment results in a supersaturated solid solution and provides the driving force for precipitation. During ageing, the supersaturated solid solution begins to dissolve/decompose first into clusters of solute atoms near vacancies. More solute dissolution occurs in mismatched Al matrix during ageing at elevated temperatures as observed by Viswanatha *et al*. (2021). Thus, it is observed that with heat treatment, the distribution of the particles and precipitated phases is more uniform and this is in agreement with the findings of Chen *et al*. (2000).

EDS profile (Figure 1(c)) confirms the result of chemical composition in Table 1. It confirms that the main elements in the matrix material are aluminium (76.21%), silicon (18.79%) and iron (1.36%).

Mechanical properties

Figures 2 (a) and (b) are the results of the tensile test and hardness (HRB) for the as-cast and heat treated samples. After heat treatment, the ultimate tensile strength (UTS)increased from 104.39 to 143 KN (improved by 37.17%) while the hardness increased from 56.13 to 78.80 HRB (improved by 40.38%). The increase in UTS and HRB was due to the precipitation of phases such as Mg_2Si and the strong interfacial bonding strength of the Al–Si eutectic phase (Singh *et al*., 2016; Li *et al*., 2019).

Conclusion

From the results analysed above, the following conclusions were made:

1. The chemical composition of the secondary Al–Si alloy showed that the Si content was 18.79 wt% above the amount for the complete dissolution of the Si during the eutectic reaction.
2. Three phases were identified in the microstructure of the Al–Si alloy: Primary α–Al dendritic phase, eutectic Si phase and intermetallic phases of Fe and Mg. After T6 heat treatment, the eutectic Si phase was spheroidized and homogeneously distributed. The primary α–Al and Si eutectic phases were observed to be well distributed and the Fe and Mg phases precipitated.
3. The mechanical properties of the samples experienced an improvement after T6 heat treatment. Ultimate tensile strength (UTS) improved by 37.17% while hardness (HRB) improved by 40.38%. This improvement may be attributed to stronger interfacial bonding of the bonding strength of primary α – Al and Si eutectic phases and precipitation of the intermetallic phases.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

REFERENCES

Alaneme, K. K., & Sanusi, K. O. (2015). Microstructural characteristics, mechanical and wear behaviour of aluminium matrix hybrid composites reinforced with alumina, rice husk ash and graphite. *Engineering Science and Technology, an International Journal*, *18*(3), 416-422.

Bhat, S., & Mahesh, B. S. (2014). Effect of heat treatment on microstructure and mechanical properties of of Al – FA – SiC hybrid metal matrix composite. *International Journal of Innovative Research in Science, Engineering and Technology*, 3(6), 13915-13920.

Chen, R., Iwabuchi, A., & Shimizu, T. (2000). The effect of a T6 heat treatment on the fretting wear of a SiC particle-reinforced A356 aluminium alloy matrix composite. *Wear*, *238*(2), 110-119.

Hurtalova, L., Tillova, E., Chalupova, M., & Durinikova, E (2012). Effect of chemical composition of secondary Al-Si cast alloy on intermetallic phases. *Machines, Technologies, Materials*, *6*(9), 11-14.

Ibrahim, M. F., Samuel, E., Samuel, A. M., Al-Ahmari, A. M. A., & Samuel, F. H. (2011). Metallurgical parameters controlling the microstructure and hardness of Al–Si–Cu–Mg base alloys. *Materials & Design*, *32*(4), 2130-2142.

Li, X., Yan, H., Wang, Z. W., Li, N., Liu, J. L., & Nie, Q. (2019). Effect of heat treatment on the microstructure and mechanical properties of a composite made of Al-Si-Cu-Mg aluminum alloy reinforced with SiC particles. *Metals*, *9*(11), Article number 1205.

Michna, Š., & Náprstková, N. (2012). The use of fractography in the analysis of cracking after formed workpiece blank mechanical machining from the AlCuSnBi alloy. *Manufacturing technology*, *12*(13), 174-178.

Pezda, J. (2008). Effect of modification with strontium on machinability of AK9 silumin. *Archives of Foundry Engineering*, *8*(special issues 1), 273-276.

Rajan, T. S., Sharma, C. P., & Sharma, A. K. (2011). *Heat treatment: Principles and techniques*. Prentice Hall of India. Pp. 314-350.

Ramadan, M. (2015). Microstructural evolution of cast hyper-eutectic Al-18% Si alloy during cyclic semi-solid heat treatment. *Journal of Minerals and Materials Characterization and Engineering*, *3*(5), 390-398.

Singh, R. K., Telang, A., & Das, S. (2016). Microstructure and mechanical properties of Al-Si alloy in as-cast and heat treated condition. *American Journal of Engineering Research*, *5*(8), 133-137.

Tillova, E., Palcek, P., & Kucharkova, L (2013). Scanning electron microscopy identification of intermetallic phases in Al - Si alloy. *Acta metallurgica Slovaca – Conference*, *3*, 196-201.

Vander Voort, G. F., & Asensio-Lozano, J. (2009). The Al-Si phase diagram. *Microscopy and Microanalysis*, *15*(S2), 60-61.

Viswanatha, B. M., Kumar, M. P., Basavarajappa, S., Kiran, T. S., & Kanchiraya, S. (2021). Effect of heat treatment and ageing on microstructure for hypoeutectic Al-7Si alloy and hybrid metal matrix composites. *International Journal of Engineering, Science and Technology*, *13*(4), 1-11.