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Effects of Yttrium Contents on the Structure, Physical, and Mechanical Properties of Al-12wt%Si Eutectic Alloy System

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Abstract
This research investigated the effects of yttrium contents on the structure, physical and mechanical properties of Al-12wt%Si eutectic alloy system. Yttrium was added in concentrations of 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0, 1.25 and 1.50wt% respectively. The samples were developed using permanent die casting method and machined to the required dimensions for the structural analysis, mechanical and physical properties tests. The mechanical properties test results confirm that the mechanical properties of Al-12wt%Si eutectic alloy system are increased with yttrium addition, with ultimate tensile strength (UTS) of 232MPa and percentage elongation of 36.7% at yttrium content of 0.7wt%. Also, impact strength of 4J and hardness of 56HBW were achieved at yttrium content of 0.8wt% and 1.0wt% respectively. Yttrium addition to Al-12wt%Si eutectic alloy system increased the electrical resistivity with maximum increase observed at 0.3wt%Y (321.6 x$10^{-6}\Omega$m). The improved mechanical properties are attributed to the structural modification of the silicon platelets.

Keywords: yttrium, Al-Si alloy, structure, physical and mechanical properties.

1. Introduction

Aluminium-silicon alloys are the most commonly used alloys in the automotive, defence and aerospace industries primarily because of their high strength to weight ratios, better castability and good surface finish. They also present good wear resistance and high welding characteristics (Lumley, 2011). Eutectic alloy composition of Al-12%Si is widely used for casting because of its high fluidity and castability (Ilona, Nwambu & Nnuka, 2016). Eutectic and near-eutectic Al–Si casting alloys attract more attention due to their excellent castability and lower cost of raw materials compared to A356 alloys (Ilona, Nwambu & Nnuka, 2016). Aluminium-silicon alloys have comparatively high fluidity in the molten state, excellent feeding during solidification, and comparative freedom from hot shortness (Mazahery & Shabani, 2014). Although silicon is an important alloying element, it solidifies as coarse and brittle platelets and so impairs the mechanical properties in cast structures (Nnuka, Agbo & Okeke, 2007). The sharp ends of this plate-like silicon act as stress raisers that initiate and propagate cracks, thereby reducing the mechanical strength of the alloy (Onyia et al. 2013; Umejiaku & Nnuka, 2015). The process of changing morphology of platelet/acicular Si to a fine fibrous form is known as modification, which results to considerable improvement in the mechanical properties. The modification of the eutectic Si can be achieved through rapid rates of solidification and by the addition of modifying agents (modifiers) to the melt (Mazahery & Shabani, 2014).

Full modification is difficult to achieve by only increasing the solidification cooling rate of the casting, which has varying section thickness and hence different cooling rates (Mazahery & Shabani, 2014). It is therefore essential to modify the eutectic structure by introducing modifying agents. Through the process of modification, this brittle, coarse and plate-like eutectic silicon structure can be transformed to fine fibrous eutectic structure with much enhanced mechanical properties (Onyia et al. 2013; Tokar, Fegyvemeki & Mertinger, 2014). Research works have been performed on eutectic modification of Al-Si alloy by using a number of elements such as those in groups IA and IIA in the periodic table, as well as the rare earth elements. It was reported that several elements such as Mn (Umejiaku & Nnuka, 2015), Mo (Onyebueke, Nwankwo & Anene, 2016), Co (Ilona, Nwambu & Nnuka, 2016), Sb (Tokar, Fegyvemeki & Mertinger, 2014) are generally used to modify the Al-Si alloy. Additionally, modification of Al-Si alloy with trace addition of several rare earth elements was also reported to result in varying degrees of refinement (Hongxu & Hong, 2014; Hu, Ruan & Yan, 2015; Knuutinen, et al. 2001; Kores et al. 2010; Milenkovic et al. 2009; Nogita et al. 2003; Nogita, McDonald & Dahle, 2004; Saleh et al. 2016; Qiu et al. 2014; Ying et al. 2015). These deleterious phases caused by plate-like silicon phase and irregular shaped iron-containing compounds are refined and modified respectively by the alloying process to develop optimum properties for engineering applications. This study is therefore a part of the research efforts geared towards investigating the effects of yttrium contents on the structure, physical and mechanical properties of Al-12wt% Si eutectic alloy system.

2.0 Material and methods

The aluminium and silicon used as the base materials for this research were 99.9% and 99% pure respectively. Yttrium with 99.9% purity was used as refiner/alloying element. The high purity aluminium was sourced locally from Cutix cable Plc, Nnewi. High purity silicon was sourced from Anyang Huatuo Metallurgy Co. Ltd, China while yttrium was sourced from Shanghai Xinglu Chemical Co. Ltd, China. Permanent die casting technique was utilized for producing the alloy samples used for this research. For the control sample (Al–12wt%Si), high purity aluminium was charged into the preheated bailout crucible furnace and heated until melting was achieved and then superheated to the temperature of 750^oC. Subsequently, pure silicon was introduced into the melt and stirred vigorously to achieve homogeneity. The mixture was left for 5mins to achieve a complete dissolution of the silicon metal. The molten metal was properly stirred again, deslagged and poured into a preheated permanent metal mould with dimension of 120mm in length and 12mm in diameter. On solidification, the casting was removed from the permanent metal mould. The remaining alloys were developed by repeating the same procedure and then addition of yttrium in concentrations of 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0, 1.25 and 1.50wt%, casting and storing for machining.

The cast samples were machined to standard dimension and stored for the mechanical and physical properties tests such as ultimate tensile strength, percentage elongation, impact strength, hardness, electrical resistivity and conductivity. The tensile strength, impact strength and hardness of the developed alloy were determined using an automated 100KN JPL tensile strength tester (Model: 130812), pendulum impact testing machine (Model: U1820) and Brinell hardness testing machine (Model: 900-355). A four-point probe electrical resistivity testing machine, Signatone, Model Quad-Pro-301-6 was utilised for the measurement of the electrical resistivity and conductivity of the developed alloy. The mounted specimens for microstructural examination were ground using P220C, P320C, P600C, and P800C grades of silicon carbide paper. The ground specimens were polished on a polishing machine using diamond paste and polishing cloth. The polished specimens were etched in Keller's reagent (95ml H_2O, 2.5ml HNO_3, 1.5ml HCl, 1.0ml HF) to reveal the specimens' surface for microstructural examination. The etched and dried specimens were finally subjected to microstructural examination using an optical metallurgical microscope (Model: L2003A) and scanning electron microscopy (SEM) (Model: EVO LS 10) at magnifications of x200 and x600 respectively.

3.0 Results and Discussions

3.1 Mechanical and Physical properties of the studied alloy

The results of the effects of yttrium contents on the structure, physical and mechanical properties of Al-12wt%Si eutectic alloy system are presented in Figures 1-3. Figure 1 showed that yttrium addition to Al-12wt%Si eutectic alloy system increased the ultimate tensile strength and hardness of the alloy by 53.3% and 20.2% respectively. Figure 2 also showed that yttrium addition to Al-12wt%Si eutectic alloy system increased the percentage elongation and impact strength by 65.83% and 166.7% respectively. Figure 2 also showed that the percentage elongation and impact strength of the alloy increased with increase in yttrium content with maximum values of 39.8%E and 4J respectively obtained at 0.8wt% yttrium content. The ultimate tensile strength and hardness of the alloy also increased with increase in yttrium content with maximum values of 231.5MPa and 56.5BHW respectively at 0.7wt% and 1.0wt% yttrium content. The significant improvement in the mechanical properties was attributed to the microstructural changes as shown in Figure 5-8. Analysis of Figure 3 showed that addition of 0.3wt% yttrium maximally increased the electrical resistivity (ρ), hence decreased the electrical conductivity (σ) of Al-12wt%Si eutectic alloy system. It was noted in Figure 3 that the addition of yttrium to Al-12wt%Si eutectic alloy system increased the electrical resistivity of the alloy by 164%, thereby decreased the electrical conductivity of the alloy by 60.9%. The increase in the electrical resistivity and corresponding decrease in the electrical conductivity will be as a result of refining effect of yttrium on the dendritic primary silicon formed in the alloy structure as shown in Figure 5-8.

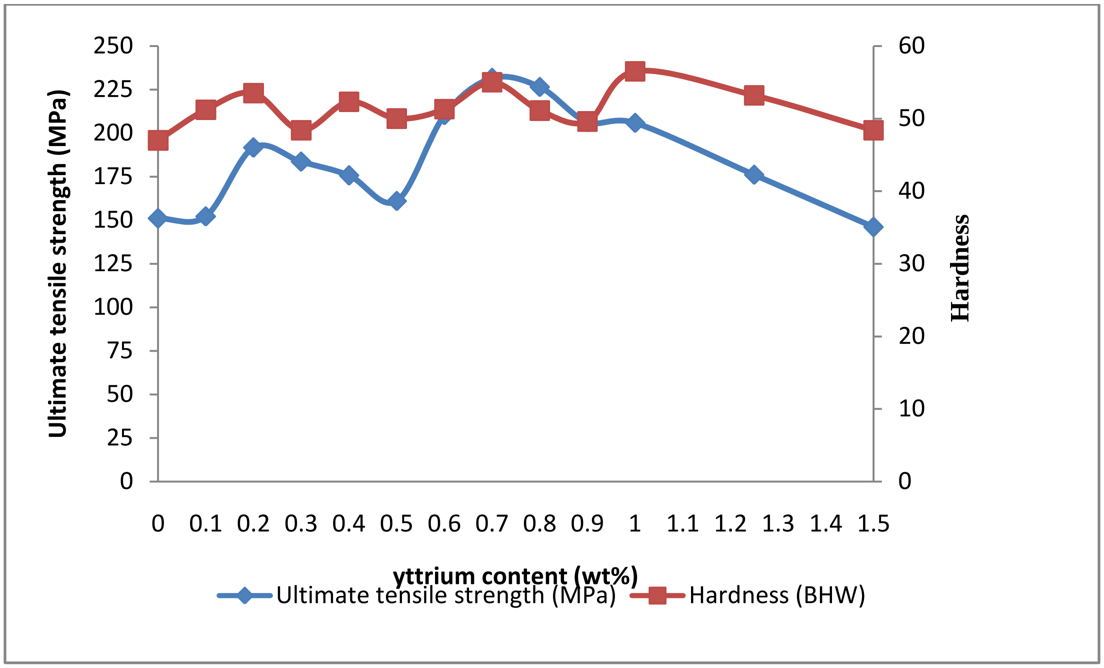

Figure 1: Effect of yttrium contents on the ultimate tensile strength (MPa) and hardness (BHW) of Al-12wt%Si eutectic alloy system

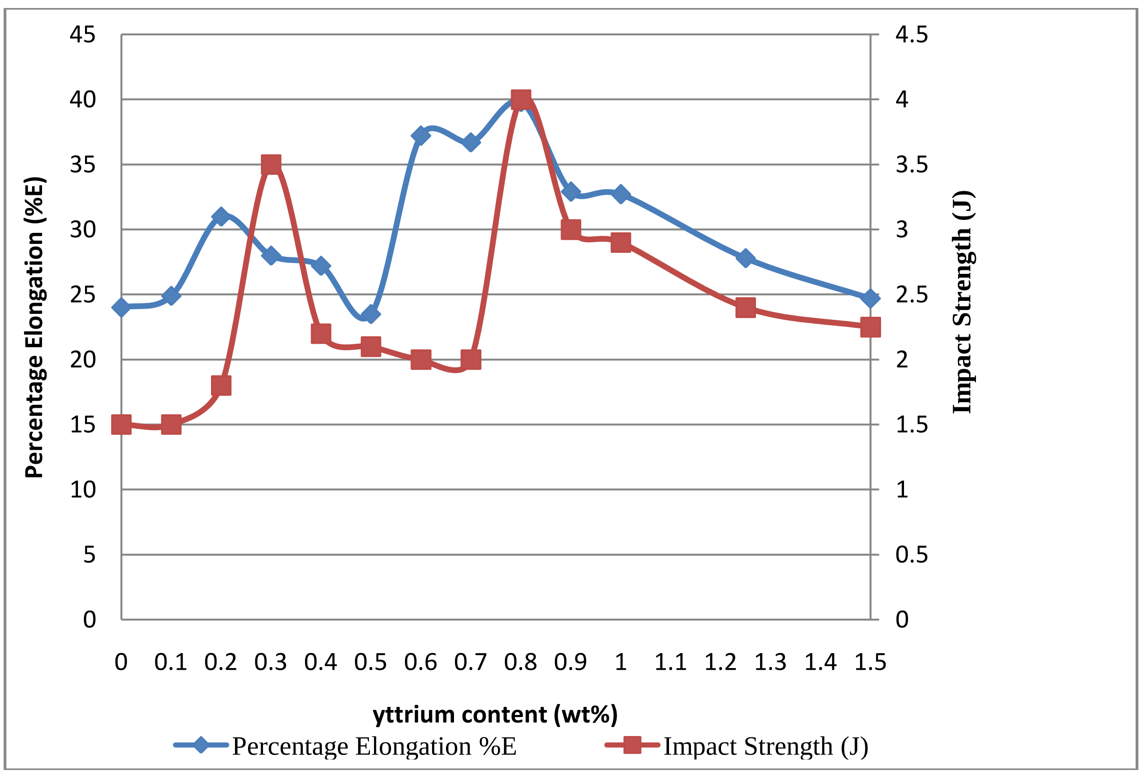

Figure 2: Effect of yttrium content on the percentage elongation (%E) and impact strength of Al-12wt%Si eutectic alloy system

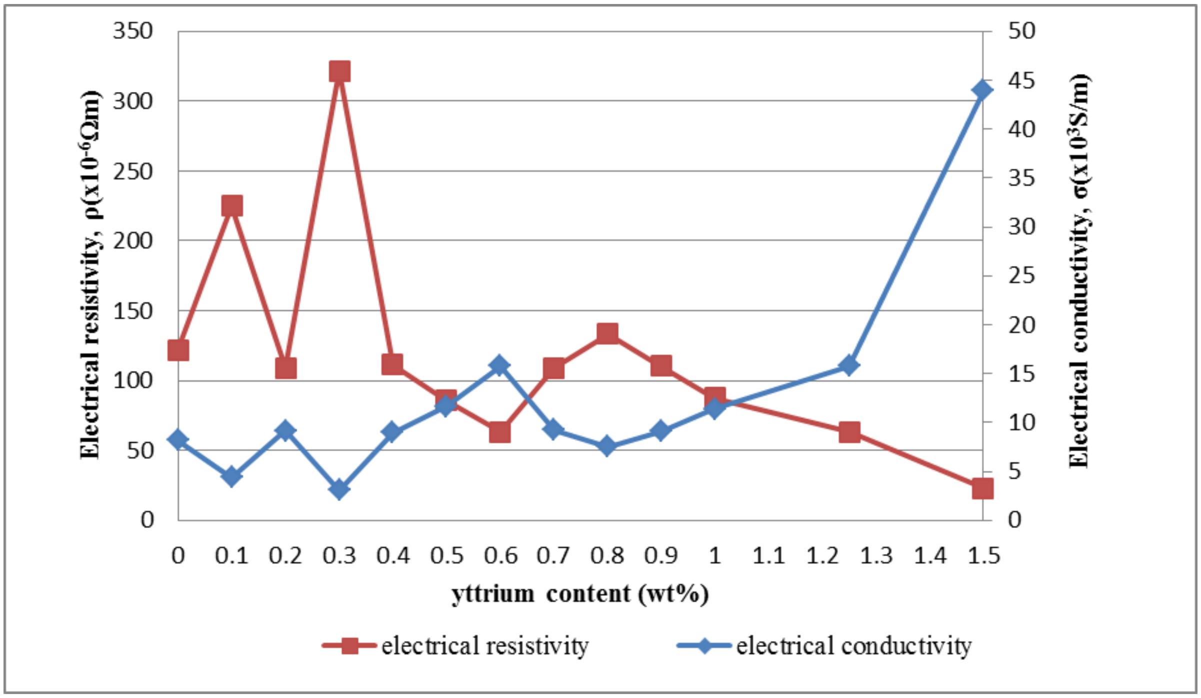

Figure 3: Effect of yttrium content on the electrical resistivity (ρ) and electrical conductivity (σ) of Al-12wt%Si eutectic alloy system

3.2 Optical and scanning electron microscopy of the studied alloy

The optical and scanning electron microscopy analyses of Al-12wt%Si eutectic alloy system with different concentration of yttrium were presented in Figures 5-8. The micrograph of the control sample presented in Figure 4 revealed the presence of coarse α-aluminium dendrite phase and plate-like coarse eutectic silicon β- phase. The micrographs of Al-12wt%Si eutectic alloy doped with different concentrations of yttrium as presented in Figures 5-8 showed that the coarse α-aluminium dendrite phase has been refined to fine equiaxed α-aluminium dendrite phase. Also, it was observed that the plate-like eutectic silicon β-phase has been refined to finer particles. The morphological changes brought about by the modification and refining effect of yttrium addition resulted in improvement of the mechanical properties of Al-12wt%Si eutectic alloy system as evidenced in Figures 1-3. It is observed in Figure 5 that the addition of 0.8wt%Y to Al-12wt%Si eutectic alloy system lead to uniform distribution of the silicon particles and the sizes of the silicon needles were refined in the structure, which in-turn increased the mechanical properties of the alloy as evidenced in Figure 1 and 2.

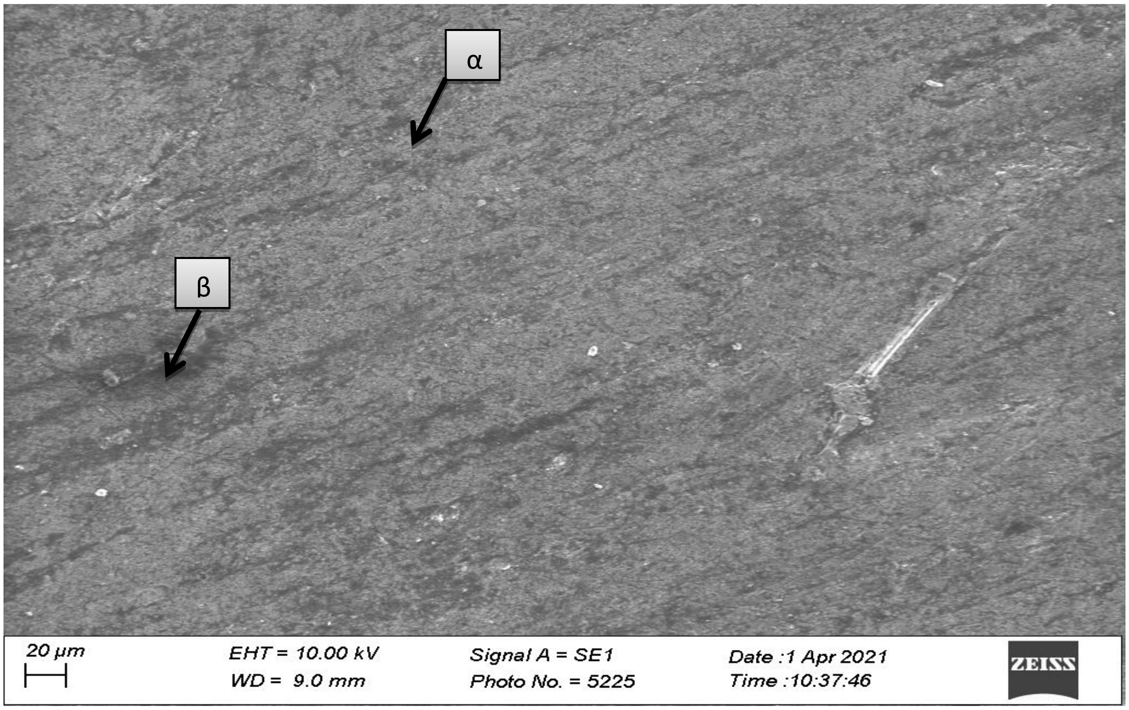

Figure 4: Scanning electron micrograph (SEM) of Al-12wt%Si eutectic alloy system (Control)

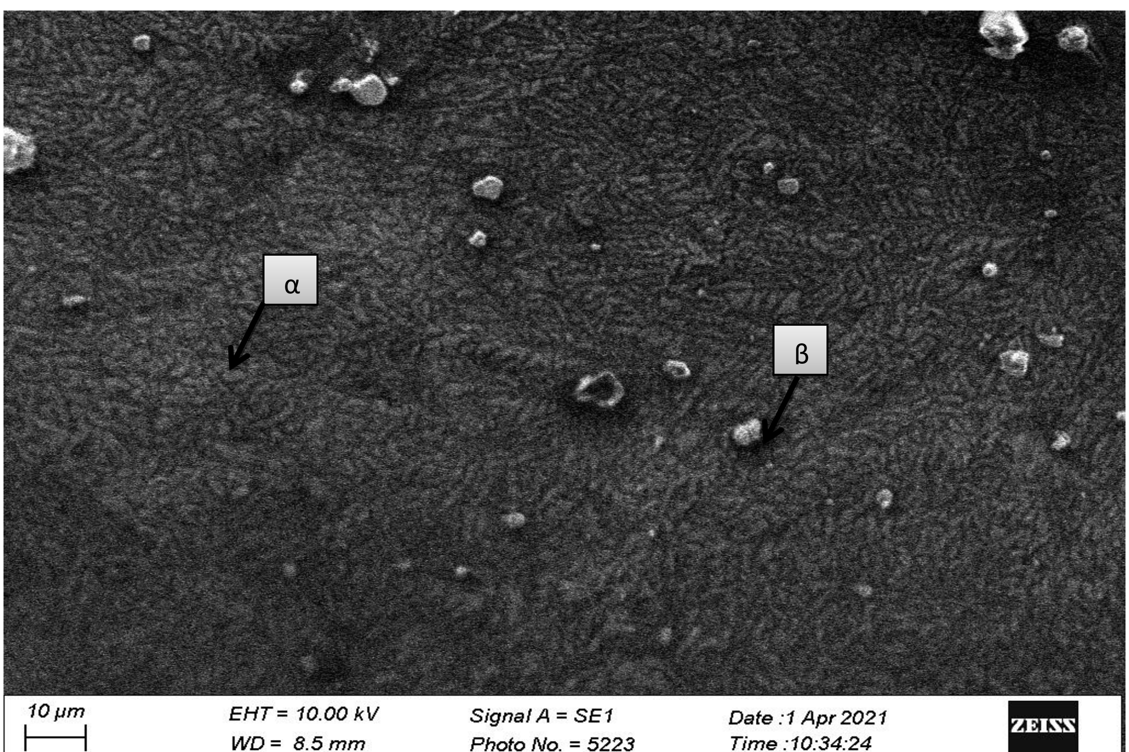

Figure 5: Scanning electron microscope (SEM) of Al-12wt%Si-0.8wt%Y eutectic alloy system

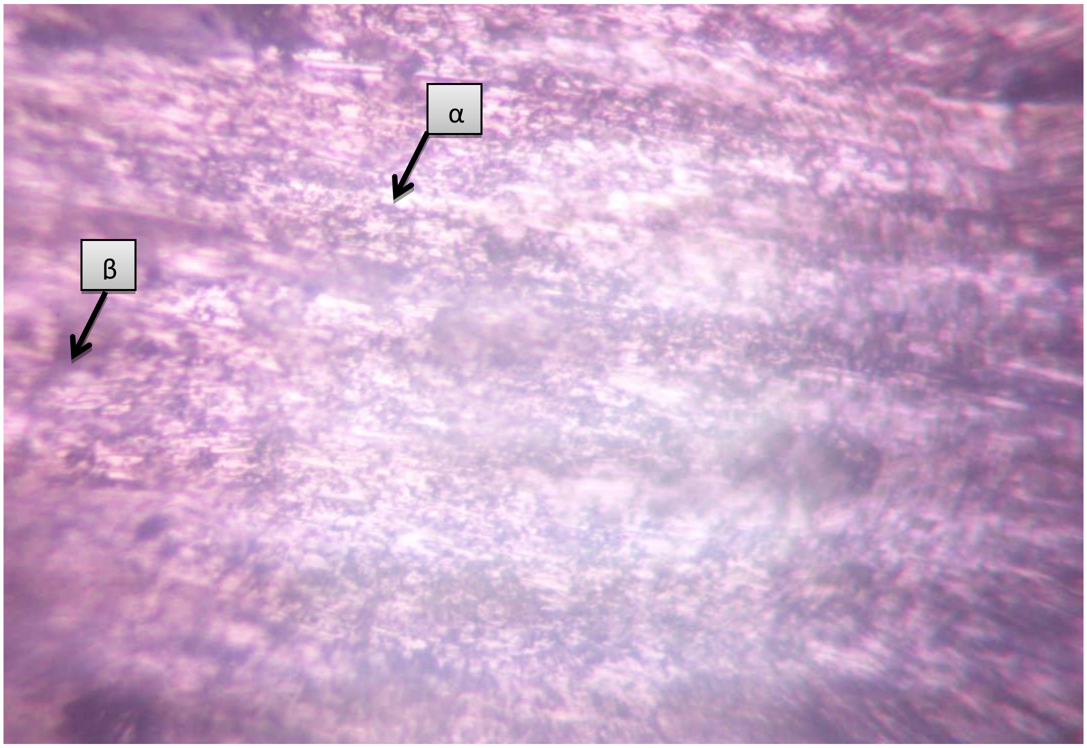

Figure 6: Optical metallurgical micrograph of Al-12wt%Si-0.3wt%Y eutectic alloy system

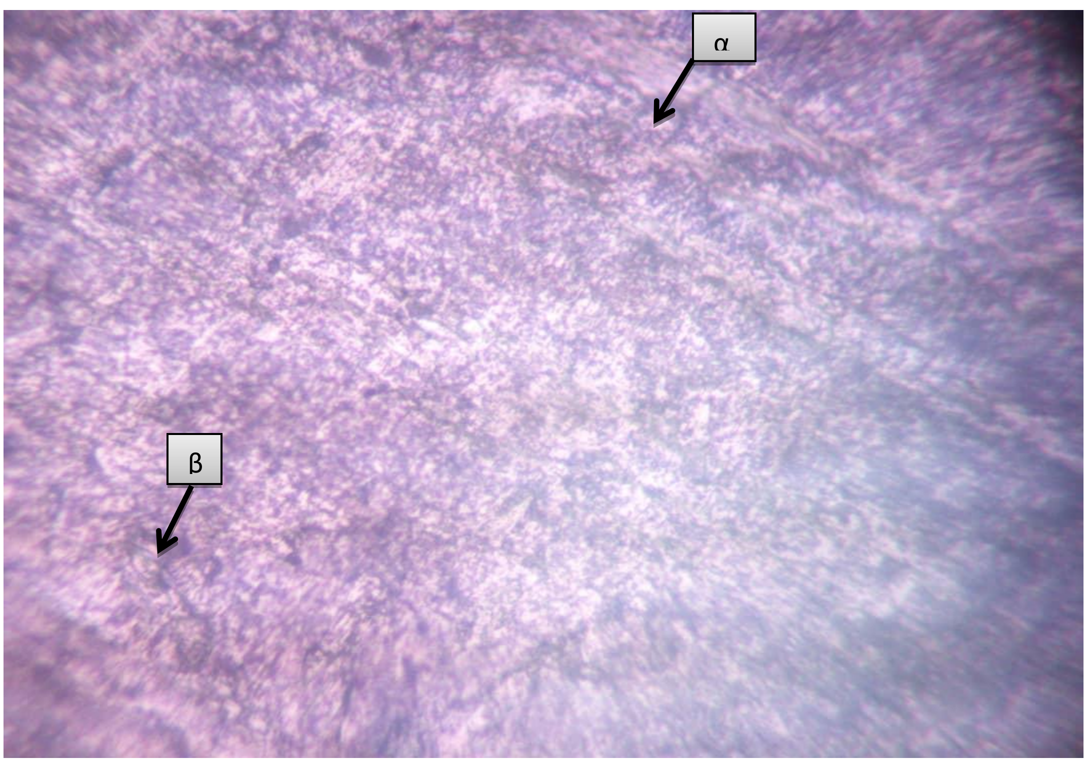

Figure 7: Optical metallurgical micrograph of Al-12wt%Si-0.7wt%Y eutectic alloy system

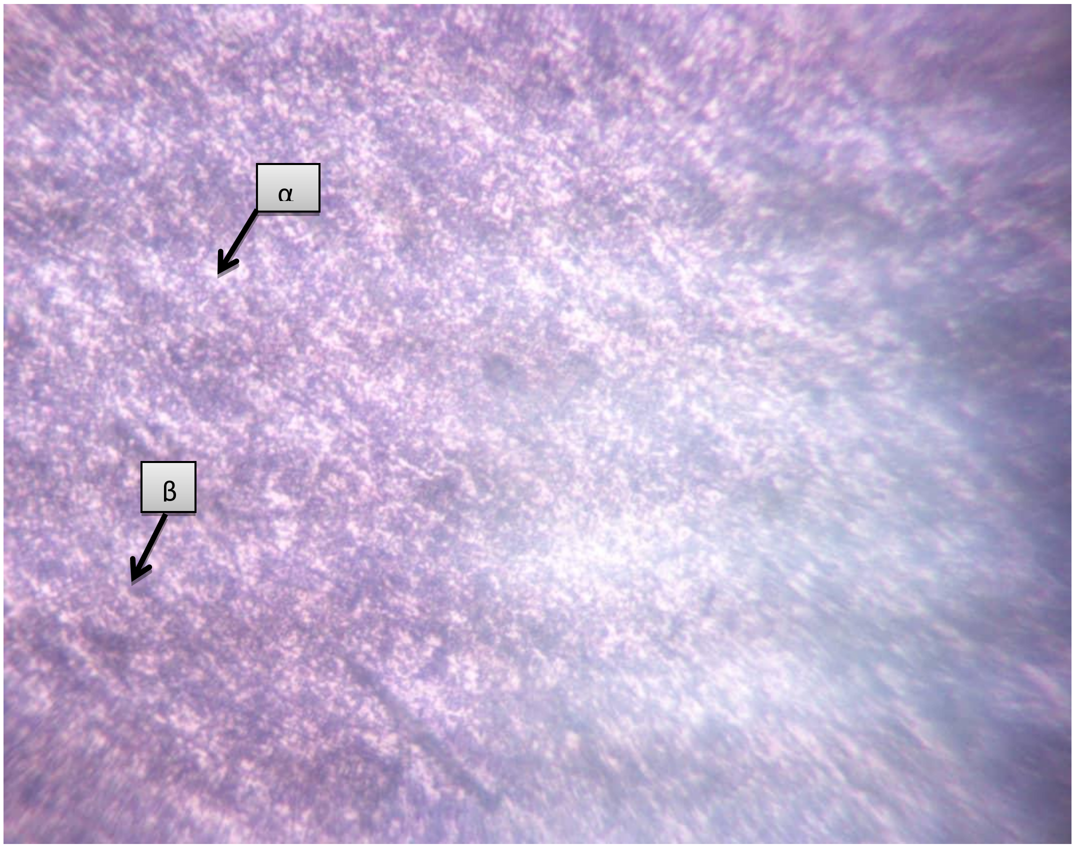

Figure 8: Optical metallurgical micrograph of Al-12wt%Si-1.0wt%Y eutectic alloy system

Contribution to knowledge

a) Al-12wt%Si eutectic alloy system with excellent ultimate tensile strength and hardness with good ductility, impact strength and electrical resistivity was developed.
b) Al-12wt%Si eutectic alloy system with refined dendritic primary silicon and modified α-aluminium dendrites was developed through alloying with yttrium.
c) Al-12wt%Si-0.8wt%Y eutectic alloy system of higher impact strength value than Al-12wt%Si-7.2wt%Co-0.23wt%Fe alloy developed by Nwambu et al. (2014) was developed through yttrium content addition.
d) Al-12wt%Si eutectic alloy system of higher ultimate tensile strength than those developed by Ilona, Nwambu and Nnuka (2016); Onyia et al. (2013); Umejiaku and Nnuka (2015); Nnuka, Agbo and Okeke (2007) was developed through alloying with 0.8wt% yttrium content.
e) Al-12wt%Si eutectic alloy system with 0.8wt% yttrium content should be utilised in lightweight component parts manufacture because of their high value of mechanical properties.

4.0 Conclusion

The following conclusions are drawn from the results of the study:

a) Yttrium addition increased the ultimate tensile strength (UTS) and percentage elongation (%E) of Al-12wt%Si eutectic alloy system from 152.2MPa-231.5MPa and 24.7%-39.8%E respectively as compared to the control specimen with UTS of 151MPa and 24%E respectively.
b) Yttrium addition increased the hardness and impact strength of Al-12wt%Si eutectic alloy system from 48.4BHW-56.5BHW and 1.5J-4J respectively as compared to the control specimen with hardness value of 47BHW and impact strength of 1.5J respectively.
c) Addition of 0.7wt%Y significantly increased the ultimate tensile strength (UTS) and hardness of Al-12wt%Si eutectic alloy system by 53.3% and 20.2% respectively. Also, 0.8wt% yttrium addition significantly increased the percentage elongation (%E) and impact strength of Al-12wt%Si eutectic alloy system by 65.83% and 166.7% respectively. The significant improvement was attributed to the modification and refinement of the plate-like eutectic silicon β- phase and coarse α-phase in the alloy structure.
d) Addition of 0.3wt%Y to Al-12wt%Si eutectic alloy system maximally increased the electrical resistivity and decreased the electrical conductivity of the alloy.

5.0 Recommendation

Further study should be carried out on the effect of combination of two different rare earth metals on the structure and mechanical properties of Al-12wt%Si eutectic alloy system.

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