Published by :
http://www.ijert.org

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 8 Issue 05, May-2019

Effect of Fe, Mn and Sr on the Microstructure and Tensile Properties of Secondary Al-Si-Cu-Mg Cast Alloys

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***Abstract*—This paper presents results on the effect of Sr, Fe and combined additions of Fe and Mn on the microstructure and tensile properties of a secondary Al-Si-Cu-Mg alloy. The microstructure features of base alloy consisted mainly of a structure with primary Al-matrix, coarse acicular Si particles and intermetallic phases such as Al_2Cu and AlCuNi. When 0.02%Sr was added to the base alloy, coarse acicular Si particles were modified to a fine fibrous form. With addition of 0.38%Fe, results in the formation of large eutectic silicon particles and Fe rich intermetallic. Moreover, when 0.45%Mn was added in combination with 0.9%Fe, the Al_2Cu, and α -AlFeMnSi with Chinese script morphology were identified. It is noticed that after T6 heat treatment, the Si particles are seen to spheroidize and fragment while the Al_2Cu phases dissolve completely. These changes lead to improved mechanical performance of the alloy. The addition of strontium decreases the ultimate Tensile strength and increases percent elongation while addition of low iron and iron with manganese decreases UTS and percent elongation in the as cast condition. T6 heat treatment increases the ultimate tensile strength while ductility decreases due to the fragmentation and spheroidization of eutectic silicon particles.**

***Keywords*— Al-Si Alloy; Cast Aluminium; Microstructure; Tensile Strength**

I. INTRODUCTION

The use of Al-Si cast alloys in automotive is developed in several countries due to their higher fluidity, good castability, good machinability and high strength to weight ratio allowing light-weighting and thus fuel efficiency and reduced emissions. Typical applications of Al-Si cast alloys are in automotive powertrain components such as cylinder heads and pistons. In this applications, the main advantage of these alloys besides their low density, is their low coefficient of thermal expansion [1,2,3]. Recycled aluminium alloys can a suitable replacement of primary produced alloys for cost reduction, energy savings and environmental and material sustainability by encouraging a closed loop system.

However, the microstructure and mechanical properties of recycled aluminum alloy are still unpredictable. This is mainly due to problems associated in controlling the chemical composition of the recycled aluminium alloys since the chemical compositions of the various scrap inputs are different. There is a need to reduce compositional effects on castability by increasing the number of alloys that can alloy direct recycling of specific Al-Si components. Several researchers [4,5,6,7,8] have been suggested that modification and heat treatment processes reduce the compositional effects on the microstructure. For instance, strontium addition plays an important role in modifying the eutectic Si morphology from needle shape to fibrous. Strontium also refines the size and morphology of Fe-bearing intermetallic phases. This leads to enhancement in mechanical properties especially tensile strength, percentage elongation and hardness [9,10].

Iron improves hot tear resistance and decreases soldering in die casting. Increasing iron above a critical content in the alloy deteriorates properties. This is because the solubility of iron is very low and tends to form intermetallic phases such as β phases, which deteriorate the mechanical performance of the alloy. Manganese is usually added to neutralize the effect of iron[11,12]. Further, large Fe-rich needles tend to block the flow of liquid metal through the feeding channels leading to formation of porosity in the casting. Mn is usually present in the Fe-containing phases and often substitutes part of Fe. Zeru et al [13] observed that increase in iron content decreased the fluidity by 21.9% due to the formation of intermetallic phases. However, addition of iron and manganese led to a reduction in fluidity by 12.1%.

For effective recycling, it is necessary to carry out detailed investigations on the effect of minor elements on the microstructure and mechanical properties of recycled cast aluminium alloys. This paper presents results from a study carried out to investigate the effect of Fe, Mn and Sr on secondary cast Al-Si-Cu-Mg alloys

II. EXPERIMENTAL METHODOLOGY

Scrap cylinder heads were melted in a 70 kg capacity oil fired graphite crucible to 720^{o}C and poured into 4 kg capacity moulds to obtain cast ingots to be used for further analysis. The chemical composition of the base alloy obtained from recycling cylinder head scrap is shown in Table 1.

TABLE 1. Chemical composition of the base secondary alloy

Base alloy	Si	Cu	Mg	Fe	Mn	Cr	Zn	Ni
	6.0	2.62	0.24	0.28	0.21	0.02	0.12	0.02
	Ti	Pb	Sn					
	0.02	0.01	0.01					

Melting of the cylinder head ingots was carried out in a 4 kg capacity graphite crucible using an electric muffle furnace. Nitrogen gas was used to degas the molten metal by immersing a ceramic tube deep into the molten metal to remove hydrogen in order to reduce porosity in the casting. Melting temperature was kept at 750^{o}C during pouring and a K-type thermocouple was employed to measure the temperature of the molten metal. Measured Fe, Sr and Mn master alloys were added to the molten base alloy at 750^{o}C to achieve target compositions. Strontium was added in the form of Al-10%Sr master alloy to achieve a 0.02 wt % strontium concentration, whereas Fe and Mn were added in the form of Al-75%Fe and Al-75%Mn master alloys briquettes, to obtain a 0.9wt % Fe and 0.45 wt % Mn concentrations respectively. After completely stirring to dissolution and homogenization of the alloy chemistry, the molten metal was skimmed to remove dross and surface oxides prior to pouring and the degassed molten metal was then poured into a permanent metal mould. The permanent metal mould was preheated to a temperature of 500^{o}C using an air circulated furnace. A ceramic foam filter was placed in the mould for each casting to minimize turbulence during mould filling and for trapping of inclusions.

After solidification, the sample bars were sectioned from different positions in order to obtain different specimens such as specimens for tensile testing and specimens for microstructure analysis. The microstructure observation and tensile tests were evaluated both in the as-cast condition and in a T6 heat treated condition. The T6 heat treatment procedure involved a solution treatment at 495^{o}C for 6 h followed by quenching in warm water at 65^{o}C, naturally aging for 24h and then artificially aging at 170^{o}C for 10 h. The samples were heat treated before machining. The specimens for microstructure observation prepared through successive grinding and polishing using standard metallography. Optical Microscopy (OP) and Scanning Electron Microscopy (SEM) were used for microstructure analysis. Compositional analysis of second phases identified by SEM was performed by Energy-Dispersive X-ray Spectrometry (EDS). The tensile test specimens were prepared according to the ASTM B557M standard with a gauge length of 25.4 mm and gauge diameter of 6. 35mm.The specimens were tested using the Hounsfield Tensometer. Six specimens were tested for each alloy obtaining six data points from which an average value was taken. After fracturing the tensile test specimens, the two pieces were reassembled and the new gauge length obtained. The percentage elongation was calculated. The yield stress was obtained based on 0.002 plastic offset strain.

III. RESULTS AND DISCUSSION

A. *Microstructure*

In order to determine the effect of additive elements on tensile properties of the Al-Si cast alloys, it was necessary to compare the microstructure of alloys investigated. Fig. 1(a), shows an optical micrograph of the microstructure of base alloy for as-cast sample obtained without additional alloying. The microstructure characterization of the base alloy consisted mainly of the Al-matrix and coarse acicular Si particles. The SEM micrograph (Fig. 1(b)) revealed the presence of intermetallic phases in the base alloy. The intermetallic phases have been confirmed by EDS analysis and are mainly Al_2Cu and Al-Cu-Ni. These kinds of intermetallic phases contribute to deterioration of mechanical properties of the alloy.

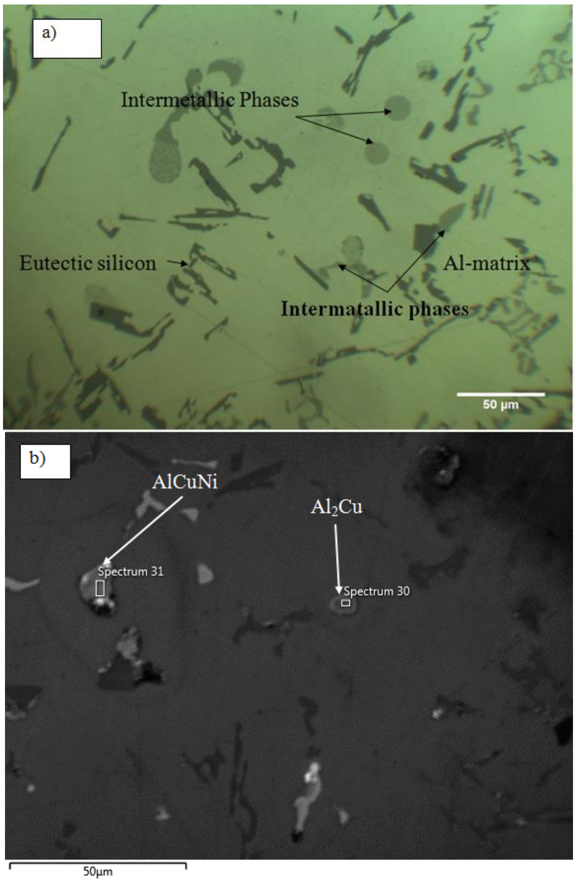

Fig. 1. As cast microstructure of the base alloy. (a) Optical image;(b) SEM image

Fig. 2 (a) presents the microstructure of the base alloy modified with 0.02 wt. % Sr. The micrograph shows that some coarse acicular Si particles were modified to a fine fibrous form; others partially modified. Intermetallic phases were also found in this alloy as shown in Fig. 2 (b). The α-AlFeMnSi were identified in this alloy as it was confirmed by EDS analysis. These phases are fine and compact due to the refinement effect of Sr in the microstructure.

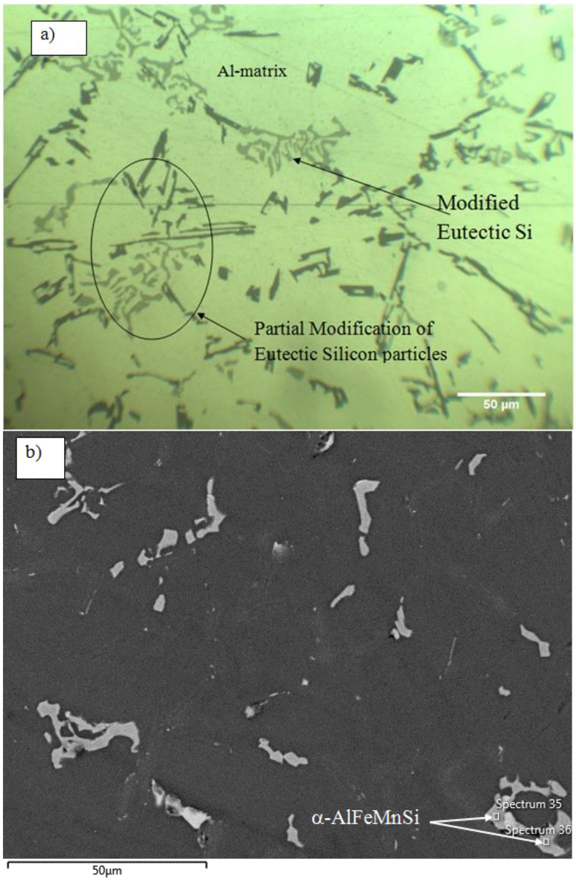

Fig. 2. As cast microstructure of the base alloy with 0.02%Sr. (a) Optical image; (b) SEM image

Fig. 3 (a) shows the microstructure of the base alloy with 0.38 wt. % Fe. The microstructure does not show much difference with that of the base alloy in Fig. 1. However, Al_2Cu and Fe rich phases were found in this alloy as shown in Fig. 3 (b).

Fig. 4(a) reveals the microstructure of base alloy with 0.9%Fe and 0.45%Mn. The optical micrographs identified acicular eutectic silicon particles and the Al matrix. Beside silicon particles and Al-matrix, SEM/EDS analysis shows the intermetallic phases, namely Al_2Cu and αAlFeMnSi with Chinese script morphology. An iron addition lead to the formation of β intermetallic phase and Mn addition eliminates the formation of β phase. Fang et al [14] reported that Mn addition decreased the detrimental effects of the Fe-rich phases by replacing it with the less detrimental Chinese script α -Fe phase, resulting in the improvement of mechanical properties.

Fig. 5(a) illustrates the microstructure of base alloy after T6 heat treatment. It was observed that the base alloy has primary Al matrix with evenly distributed intermetallic phases, fragmentation of eutectic Si particles and eutectic Si particles. Si particles also appeared as coarser acicular shape due to the size and shape of particles. Eutectic Si was observed as long particles. The spheroidization and coarsening of particles is dependent on their initial sizes and shapes. The small particles are fast spheroidized and vice versa. Fig. 5 (b) shows intermetallic phases observed using SEM/EDS analysis. The Iron intermetallic, eutectic Si particles and Al-matrix Phases were identified.

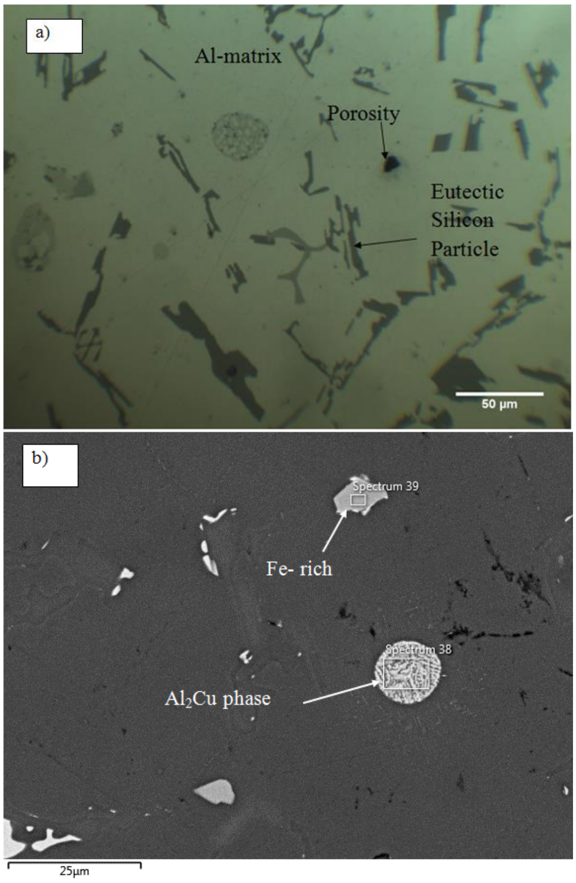

Fig. 3.As cast microstructure of the base alloy with 0.38%Fe.

Fig. 6 (a) shows the microstructure of base alloy modified by 0.02% Sr after T6 heat treatment. The micrograph of this alloy indicates the aluminium matrix surrounded by spheroidised eutectic Si particles and intermetallic phases. The micrograph revealed that the size of eutectic silicon particles is small and more compacted which led to a fine microstructure. The modifications of intermetallics were also fragmented. It has been reported that the addition of strontium changed the eutectic Si morphology from acicular fibrous to round thereby refining the morphology of intermetallic phases [9].

The microstructure of the alloy with 0.38% is shown in Fig. 7. The optical micrograph of this alloy shows primary Al- matrix surrounded by fragmented of silicon particles and intermetallic phases. Spheroidization of the eutectic silicon particles is not observed in this alloy after T6 heat treatment. The increase of iron to 0.38 wt. %Fe is seen to significantly increase the size of the eutectic silicon particles. SEM/EDS indicate AlFeMnSiCu and Fe intermetallic phases in this alloy.

Fig. 8. illustrates the microstructure of base alloy with 0.9%Fe and 0.45%Sr after T6 heat treatment. Two phases namely, Iron intermetallic and αAlFeMnSi phases were identified by using SEM/EDS.

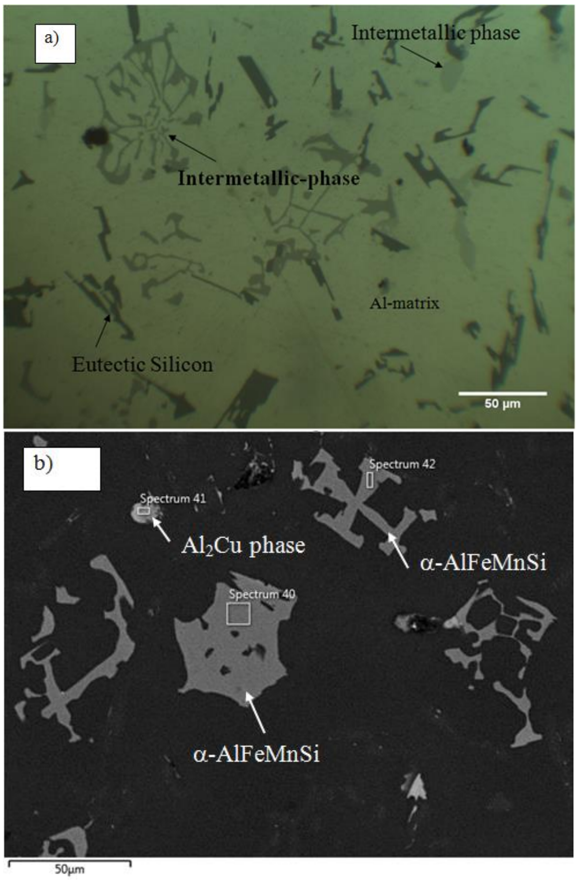

Fig. 4.As cast microstructure of the base alloy with 0.9%Fe and 0.45%Mn. (a) Optical image; (b) SEM image

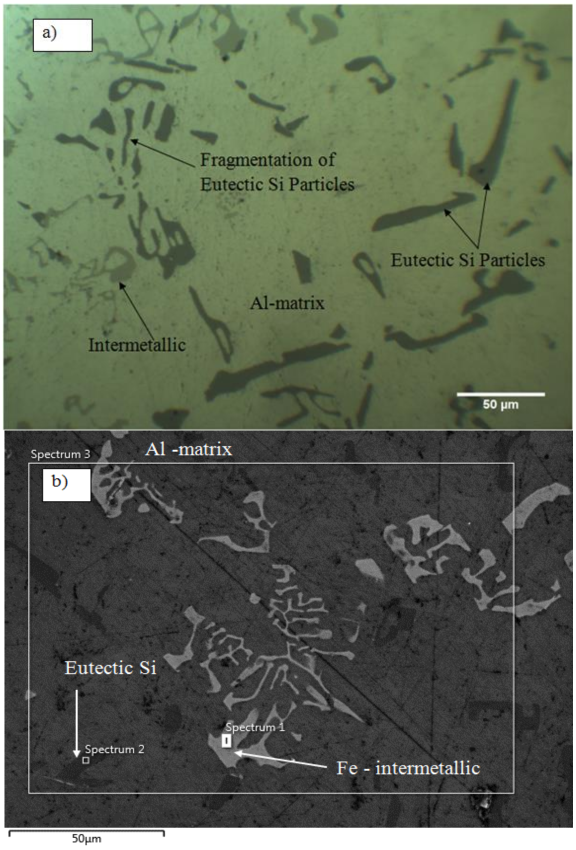

Fig. 5. Heat treated microstructure of the base alloy. (a) Optical image; (b) SEM image

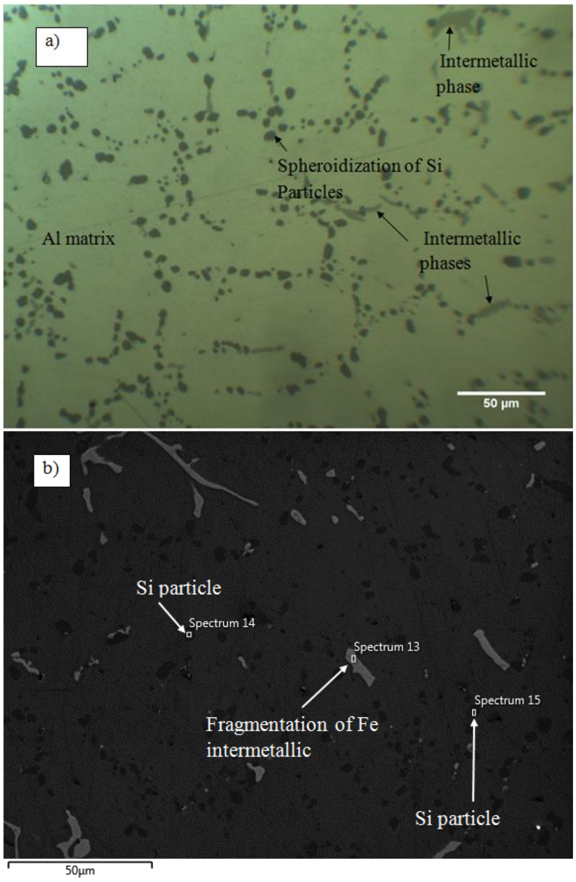

Fig. 6.Heat treated microstructure of the base alloy with 0.02%Sr. (a) Optical image; (b) SEM image

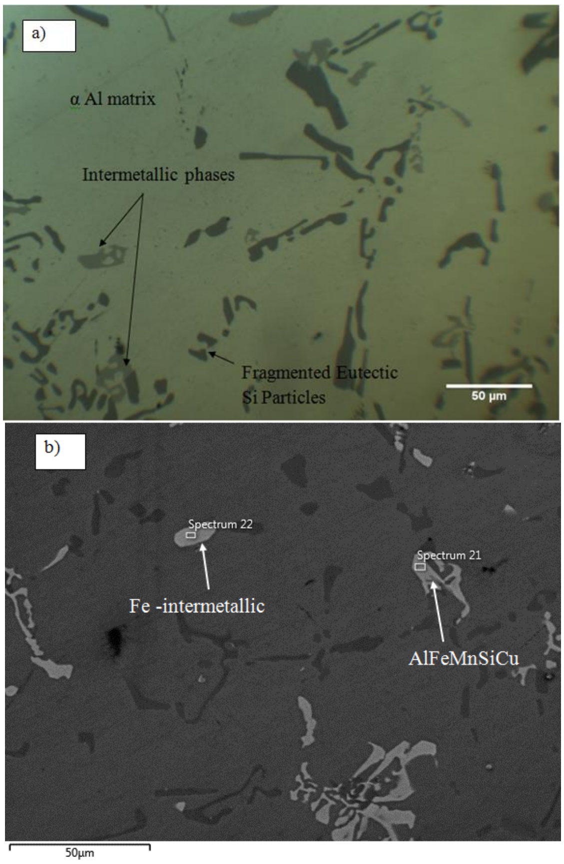

Fig. 7. Heat treated microstructure of base alloy with 0.38%Fe. (a) Optical image; (b) SEM image

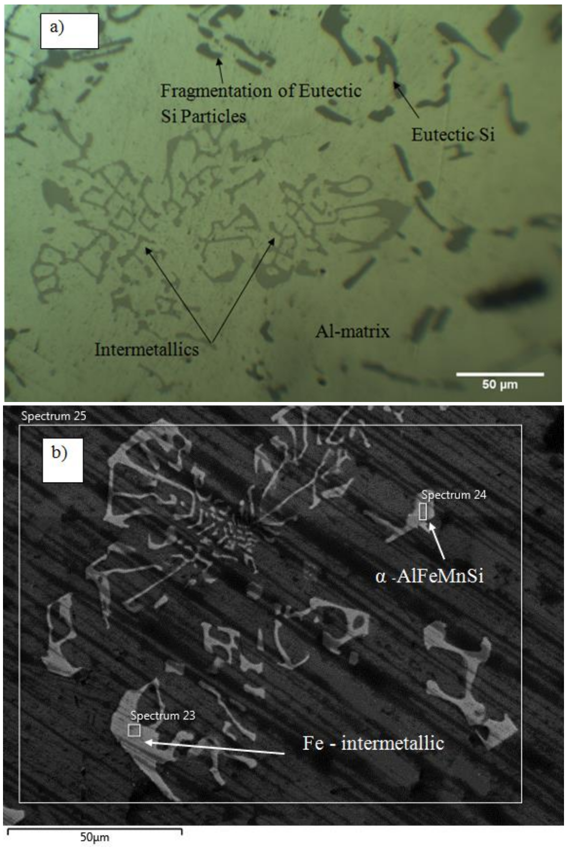

Fig. 8.Heat treated microstructure of the base alloy wit 0.9%Fe and 0.45%Mn. (a) Optical image; (b) SEM image 3.2 Tensile Strength

B. *Tensile Strength*

Fig. 9: shows the average ultimate tensile strength (UTS) values of the base alloy, alloy with 0.02%Sr, alloy with 0.38%Fe and base alloy with 0.9%Fe and 0.45%Mn in as cast alloys. It was observed that the average values of UTS were 209.5MPa, 203.6 MPa, 195.4MPa and 201.5MPa respectively. The addition of 0.02%Sr was found to decrease the UTS by 2.8% while increas of Fe to 0.38% decreased UTS by 6.73%. However, with 0.9%Fe and 0.45%Mn the UTS decreased by 3.8%. The strontium modification indicated reduction in ultimate tensile strength. This reduction is due to the power of strontium addition that could generate porosities during casting. Dong et al [15] reported that Sr modifier added to the melt, was observed to increase amount of porosity in the casting.

The addition of Fe level of 0.38% in the base alloy was observed to decrease UTS by 6.73% in as cast state. Increasing iron content in the alloy led to the formation of intermetallic phases Al_2Cu and Fe rich phase, which contributed to the degradation of the mechanical properties due to their poor bonding strength with the matrix [11] and their effect as stress raisers. It may also increase the porosity in the casting due to the blocking the channels that feed solidification shrinkage.

It was observed that combining 0.9%Fe and 0.45%Mn in the base alloy decreased UTS by 3.8% in as cast alloy. The addition of Fe and Mn to the base alloy led to better UTS than the addition of Fe to the base alloy. This is because of the neutralizing effect of Manganese on Fe. The iron rich intermetallic phase was transformed to αAlFeMnSi with Chinese script morphology that has probably less harmful effects on the mechanical properties.

After T6 heat treatment, the average UTS of the alloys is indicated to increase by 89.6%, 54.3%, 64.8% and 57.5% respectively as compared to as cast alloys. The addition of strontium increased UTS by 54.3%, and this was due to the spheroidation of the eutectic Si particles and fragmentation of iron intermetallic phases. Similar results obtained by Peng et al [16] reported that the UTS is influenced by the spheroidation of eutectic silicon particles and dissolution of intermetallic phases.

Heat treatment was observed to improve the UTS for all alloys investigated, this was due to the age-hardening that enhances the change in microstructure by spheroidization and coarsening of eutectic silicon, shortening and thinning of intermetallic phases. The dissolution of precipitates and the precipitation of finer hardening phase resulted in the increase in the tensile strength in the alloy [17].

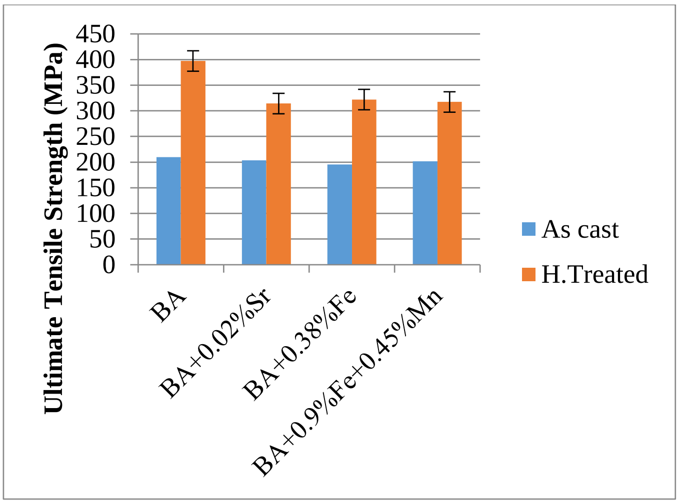

Fig. 9.Average ultimate tensile strength of alloys investigated

C. *Percentage Elongation*

Fig.10 illustrates the average percentage elongation of the alloys in the as-cast condition. It was observed that the average percentage elongations are 1.45%, 1.83%, 1.11% and 1.31% for the base, Sr-modified and for the low and high Fe alloys respectively. It can be seen that the base alloy modified by 0.02% Sr, the percentage elongation of the alloy increased by 26.2% while for 0.38% Fe, the percentage elongation of the alloy decreases by 23.5%. .With 0.9%Fe and 0.45%Mn addition, the percentage elongation of the alloy decreases by 9.7%.

Fine eutectic silicon particles and distribution of intermetallic phases in the casting resulted in improving the ductility [6]. The addition of strontium increased ductility in Sr-modified alloy due to modification of eutectic silicon particles. Acircular structure of the unmodified eutectic silicon particles and brittle intermetallic phases resulted in inferior mechanical properties such as percentage elongation and strength. This is because they easily break due to their brittleness.

After T6 heat treatment, the percentage elongation values of the base alloy, the Sr modified alloy, the low Fe and the alloy with Fe+Mn is indicated to decrease by 25.5%, 45.5%, 17% and 31% respectively. It was noticed that changes in alloy chemical composition caused slight effects on the percentage elongation of the alloys. During heat treatment, the hardness of the matrix can cause reduction in % elongation of alloys. In the current study, the base alloy with 0.38%Fe was observed to have the smallest value of percent elongation after T6 heat treatment. This was attributed to the large eutectic silicon particles observed in this alloy after heat treatment, which could significantly cause the failure of a material in the form of brittle fracture, thereby resulting in low ductility. Casting porosity may also have negative effect on tensile strength and ductility of alloys.

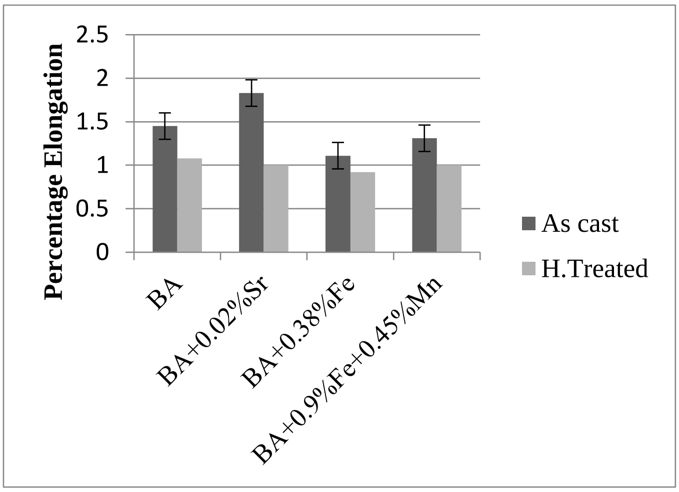

Fig. 10.Average percentage elongation of alloys investigated

CONCLUSION

Addition of Sr, Fe and Mn on the microstructure of a secondary Al-Si-Cu-Mg alloy indicated that alloying elements have significant influence on the microstructural features of the alloy. The microstructure features of base alloy consisted mainly of a structure with primary Al-matrix, coarse acicular Si particles and intermetallic phases such as Al_2Cu and Al-Cu-Ni. When 0.02%Sr was added to the base alloy, coarse acicular Si particles were modified to a fine fibrous form. With addition of 0.38%Fe, results in the formation of large eutectic silicon particles and Fe rich intermetallic phase. Moreover, when 0.45%Mn was added in combination with 0.9%Fe, the Al_2Cu, and α -AlFeMnSi with Chinese script morphology were identified. It is noticed that after T6 heat treatment, the Si particles are seen to spheroidize and fragment while the Al_2Cu phases dissolve completely. These changes lead to improved mechanical performance of the alloy.

The addition of strontium decreases the ultimate Tensile strength and increases percent elongation while addition of low iron and iron with manganese decreases UTS and percent elongation in the as cast condition. T6 heat treatment increases the ultimate tensile strength while ductility decreases due to the fragmentation and spheroidization of eutectic silicon particles.

ACKNOWLEDGMENT

The authors would like to express their appreciation to the METEGA for their sponsorship and research facilities from Jomo Kenyatta University of Agriculture and Technology, and University of Nairobi.

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