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The effects of modification of the structure of iron and silicon on the mechanical properties of Al - 12% Si alloy

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Abstract

The modification effects of the structure of iron by manganese, cobalt and molebdenumn and silicon by sodium have been studied in Al - 12% Si alloy. The mechanical properties used to assess the effects of the structural modification were ultimate tensile strength, relative elongation and hardness. Chemical and micro-structural analyses were also conducted. Standard mechanical testing equipment were used for determining the mechanical properties, while chemical analysis was conducted by the wet analytical technique. Micro-structural analysis was done using the metallurgical microscope. Results obtained from the study showed a correlation between iron removal, structure of silicon and the mechanical properties of the studied alloys. The results of chemical analysis and micrography confirmed the modifying effects of sodium and silicon and the consequent enhancement of the mechanical properties of AI-12% Si alloy. The ratios of iron to the correcting elements at which the optimal values of UTS were obtained was also established for the studied elements.

1. Introduction

The aluminum - silicon alloy system constitute an important engineering material that finds application in many areas. The alloy system is indispensable in the manufacture of agricultural machinery, automobile, military equipment, shipbuilding and aerospace components and spare parts.

Silicon imparts high fluidity and low shrinkage to the AI-Si alloy system resulting in good castability and weldability (Nnuka, 1985). The low expansion coefficient is exploited in the production of pistons and the hardness of silicon particles for wear resistance (Mondolfo, 1976). The high fluidity conferred on the Al - Si system accounts for its preference by foundrymen (Hellawell and Touloni, 1976). The AI-Si alloy system possesses high shock and corrosion resistance thereby finding application in the shipbuilding, aerospace and tractor industry. .

The AI-Si system contains iron as an inherent but deliterous impurity. Silicon itself solidifies as platelets, which act as strain raiser. The iron containing compounds formed by the AI-Si system for example $FeA1_6$, $FeAl_3$, Fe $SiAI_8$, Fe_3Si_2 Al_{15} etc are brittle. The combined effect of the brittle compounds and silicon platelets is a reduction in mechanical properties (Benersky et al., 1988). The cheapest and the most effective way to correct the effects of silicon and iron in the AI-Si system of alloys is to modify the structure of silicon and to recompact the structure of the iron - containing compounds. Both processes are conducted while the alloy is in the liquid state. It is known (Benersky et al., 1988) that sodium in the quantity of 0.0 I % weight. of the alloys reduces the brittfeness of the alloy, by modifying the structure of the silicon platelets. Sodium and litium increase the surface tension of the liquid alloy and block the directional growth of the silicon crystals, thereby modifying the structure (Sigwort, 1983; Hanna et al., 1984). Sodium is usually introduced into the melt in the form of Na CI or and Na F in the quantity of 2/3 Na F + 1/3 Na CI in the laddie (Nnuka,1985).

On the other hand the deleterious effect of iron is corrected by the addition of manganese, cobalt and molybdenum to the liquid alloy in the furnace. The amount of iron present is confirmed by chemical analysis of the liquid alloy and the correcting dopants are added in the ratio of Fe: Mn, Mo, Co = 1: 1. The dopants act to mill down the structure of the brittle compounds and to re-compact them in forms that are regular and hence enhance better mechanical properties (Nnuka, 1989).

The overall effect of modification and correction of the effects of iron is the production of high quality AI-Si alloys

that comply with the demands on mechanical properties. Complex alloying is sometimes employed to further improve the mechanical properties of silumins as the AI-Si alloy system is called. Alloys for military applications are known to have been produced by injecting copper, zinc, titanium, magnesium, nickel, ceruim, calcium, tin, lead, bismuth, germanium and others into silumins (Nnuka, 1985). An alloy of known composition produced by the process stipulated above has been used to manufacture amphibian tanks for military application.

The ratio of iron to the correcting elements(C.E) was known to be F e:CE= 1: 1. But Agbo (2003) showed that the ratio was Fe: Co = 1: 1 but ratio for Fe: Mn, Mo was 1:2. The ratio is quite important because it ensures economy of expensive dopants, thereby significantly reducing the cost of production and conserving scarce metals. It is for the stated reasons that efforts on establishing the true ratio of iron to the dopants is an effort in the right direction hence a justification for the study.

2. Materials and methods

2.1 Materials

The materials used in the study are from different sources within Nigeria as indicated in Table 1.

Table 1
Sources of the materials used for the study.

S/N	Element	Source	Remark
1.	Aluminum	Aluminum Smelter Co. Ikot-Abasi	99.9%AI
2.	Silicon	Industrial Training Center Zaria	99.5%
3.	Sodium Chloride	National Metallurgical Development Center, Jos.	99.5% Na
4.	Manganese (Electrolytic)	Bamford Foundries, Jos.	99% Mn 1 % others
5.	Molybdenum	Mining Corporation, Jos	99.9%Mo
6.	Cobalt	Emole Chemical Laboratory, Makurdi.	98% Co 1.5%, Fe, 0.5% others

2.2 Methods

Standard methods were used to determine tensile strength, hardness chemical composition and micro-structural analysis. Tensile strength was determined using the Tinus Olsen Model 290 universal testing machine with a digital indicator. The 300kN load capacity comprised of the straining and the recording units.

The Vick test model 18506 Vickers hardness universal testing machine was used to determine the hardness of the alloys.

Chemical composition was determined using wet analytical method. Ten to twelve pellets of sodium hydroxide and a pinch-off sodium carbonate were added to 0.1 gm finely dried sample in a nickel crucible, which was kept over a hot plate to melt and finally fused over a low flame at a temperature of 600°C in the furnace. The crucible and its content were allowed to cool in air before transferring to a 250ml beaker. 100 ml of hot water was slowly added and then boiled for 10 minutes. The sample was removed from the furnace, while the crucible was withdrawn with a glass rod, washed thoroughly and the boiled water transferred into the 250ml beaker.

The water was poured into a 400ml beaker. 20 ml concentrated hydrochloric acid was added and the content dissolved on a hot plate. The hot solution was filtered through a 40 NQ What-man filter paper into a conical flask. 10ml of the filtrate was poured into a 100ml volumetric flask and distilled water was added to make-up to the mark. The content of the 100ml volumetic flask was transferred into a 500ml conical flask and the precipitate was washed 5 times with hot water to ensure complete removal of the sodium aluminates.

After cooling, 25ml of acetic acid-aluminum acetate buffer solution was added. The volume was topped to 200ml with water in a 500ml conical flask. The pH was adjusted from 5.0 to 5.5 by adding the buffer and the solution was again boiled for 10 minutes. After cooling, 3 drops of xylenol orange indicator was added with a lemon yellow colour developing. The solution was titrated with standard zinc acetate solution. The colour changed at end point from lemon yellow to purple.

Micro-structural analysis was conducted using a metallographic microscope type PM 16 which was fitted with a camera. The specimen were ground using silicon carbide belt grinder (120 grit). They were subsequently roll ground using finer silicon carbide grit 240, 320, 400 and 600 respectively. The final grinding was done with grit 1000 silicon carbide roll grinder. The specimen were polished with magnesium oxide. The etchant comprised of 0.5% hydrofluoric acid, 1.5% hydrochloric acid and 2.5% nitric acid in aqueous solution. Etching was done at room temperature for 3 - 5 minutes. Micrographs were observed at magnifications of 100X, 200X and 500X while photographs were snapped at magnification of 100X.

3. Results

The results of the study are presented in Tables 2 - 4 and Figures I - 13.

4. Discussions

Results on Table 2 show the mechanical properties of the

Table 2
Mechanical properties of eutectic AI-Si alloys doped with Mo, Co, and modified with Na.

Alloy	Mechanical Properties		
	UTS (N/mm^2)	Elongation (%)	Hardness (Hv)
AI-Si	101.3	6.3 .	618
Al -Si +0.9%Mo	104.0	12.9	62
AI-Si + 1. 7%Mo	118.0	12.9	637
AI-Si + 3.5%Mo	124.0	12.5	656
AI-Si + 4.3%Mo	120.0	12.7	654
AI-Si + 0.9%Co	129.0	12.7	648
AI-Si + 1.7%Co	138.6	12.2	663
AI- Si + 3.5%Co	136.8	12.4	658
Al - Si +4.3%Co	134.8	12.7	655
AI-Si +0.9%Mn	115.6	13.6	630
AI-Si +1.7% Mn	121.3	13.1	640
AI-Si +3.5% Mn	128.4	12.7	649
AI-Si + 4.3% Mn	127.5	12.9	643
AI-Si + 3.4%M +2.3%Na	157.4	10.9	678
AI-Si + 1.75 Co +2.3%Na	161.3	10.1	697
AI-Si + 3.4%Mn +2.3%Na	159.4	11.1	680

Table 3
Chemical composition of eutectic AI - 12% Si alloy corrected for iron with Mo, Co and Mn

Alloy	Chemical composition, %							
	Al	Si	Fe	Mo	Co	Mn	Mg	Others
AI- Si + 0.9%Mo	84.85	12.56	0.90	1.00	0.02	ND	0.09	0.5
AI- Si + 1.7%Mo	84.61	12.50	0.75	1.40	0.01	0.02	0.11	0.70
AI- Si + 3.5%Mo	84.61	12.51	0.58	1.68	0.02	0.02	0.08	0.70
AI- Si + 4.3%Mo	84.59	12.50	0.61	1.65	0.02	0.02	0.09	0.52
AI-Si + 0.9%Co	84.76	12.48	0.46	0.01	1.46	0.02	0.11	0.62
AI-Si +1.7%Co	84.67	12.48	0.22	ND	1.77	0.02	0.08	0.76
AI-Si +3.5%Co	84.74	12.51	0.36	0.01	1.68	0.02	0.09	0.59
AI-Si + 4.3%Co	84.68	12.50	0.38.	0.01	1.66	0.02	0.09	0.52
AI- Si + 0.9%Mn	84.93	12.55	0.80	0.01	0.01	1.48	0.08	0.14
AI-Si + 1.7%Mn	84.93	12.54	0.69	0.01	0.02	1.55	0.1	0.16
AI-Si + 3.5%Mn	84.98	12.55	0.42	0.02	0.02	1.72	0.1	0.19
Al-Si + 4.3%Mn	84.97	12.54	0.40	0.02	0.02	1.70	0.1	0.25

Table 4
Chemical composition of eutectic AI - 12% Si alloy corrected for iron with Mo, Co and Mn.

Alloy	Chemical composition, %								
	AI	Si	Fe	Mo	Co	Mil	Mg	Na	Others
AI-Si + 3.4%Mo + 2.3% Na	83.60	11.55	0.58	0.68	0.02	0.02	0.08	2.28	0.19
AI- Si + 1.7%Co +2.3% Na	83.67	11.68	0.22	ND	1.77	0.02	0.08	2.26	0.30
AI-Si + 3.4% Co + 2.3% Na	83.76	11.55	0.42	0.02	0.02	I. 72	0.01	2.22	0.19

studied alloys. From the table, molebdenum showed an insignificant increase in the ultimate tensile strength (UTS) as compared to the parent alloy (AI - Si). An increase of 2.7% was noted for the ratio of Fe: Mo = 2: I. Table 3 showed that the composition of iron was 0.9% and so the removal of iron at the ratio was relatively low. At the ratio of Fe: Mo = I: I, the percentage increase in UTS rose to 16.5% and was equally low since the iron content was still above the tolerable limit for cast silumins. At a ratio of Fe:Mo = 1:2, UTS increased by 24.4% while the iron content was reduced to 0.58% (a tolerable limit) for silumins.

Cobalt increased the UTS by 27.3% for a ratio of Fe: Co = 2: 1 thereby reducing the content drastically to 0.46%. At the ratio of Fe: Co = I: I, the UTS increased by 36.8% and the iron content further reduced to 0.22%. However for the ratio of Fe: Co = I :2, the UTS was 35% above the parent silumin at iron content of 0.22%.

From Table 2, it was noted that the relative elongation for the studied alloys decreased as the UTS increased. The observation was true for manganese, cobalt and molebdenum corrected silumins. The phenomenon was believed to be largely associated with silicon distribution and its particle shape. The hardness results showed the same pattern as those for UTS with cobalt giving the highest value as compared to manganese and molebdenum. Table 3 showed the chemical compositions of the studied alloys. The iron content was noted, especially the reduction in content as the quantity of the correcting elements increased. Table 4 showed the chemical composition of the optimally corrected alloys further modified with 2.3% Na. The iron content was noted to be 0.58%, 0.22% and 0.42% for the silumins corrected optimally with Mo, Co and Mn respectively.

The results of the microstructure and metallography Tables I to 13 showed that indeed correction of the iron content and the structural modification consequent upon it was observed. The finger - like spikes of the brittle compound $FeSiAl_5$ observed in the eutectic Al - Si alloy (plate I) were corrected with the addition of the various correcting elements (Mn, Mo, Co). Plates 2 to 10 displayed remarkable varieties of morphologies exhibited by silicon crystals in Al - Si alloys. Plate 2 revealed that the silicon phase led the aluminum phase by a large margin at the growth interface with the little modification with Mo but in plates 3 and 4 the predominance disappeared as the modification level increased, showing a possible tendency for the aluminum to over-grow the silicon. plates 5 to 7 displayed the eutectic alloys corrected for iron with cobalt. Primary nucleated silicon phase clustered together (Plate 5) confinning its lead at the growth inter face. However, increased quantity of cobalt showed a reversal with a possible aluminum lead and the growth interface with silicon finely dispersed at the background and grain boundaries (plates 6 and 7). Plate 6 revealed a finely distributed structure of nearly equal grain sizes. Plates 8 to 10 showed eutectic AI-Si corrected for iron with manganese. A fairly even distribution of silicon was revealed with plate 10 showing better grain size structure. Some coarsening effect was however observed in Plate 9. Results of the micrographs of the corrected alloys with optimal UTS further modified with sodium were displayed in Plates II to 13. Partial spheroidization was observed (Plate 11) with continuous silicon phase in - between grain blocks. Greatly reduced equiaxed round crystals all through the structure with finely distributed silicon crystals both at grain foundries and through the matrix were noted in Plate 12. In Plate 13 spheroidized silicon crystals interspaced with aluminum were displayed. Spheroidization is known to occur consequent upon increased surface tension caused by sodium resulting to suppression of the finger - like spikes that crystallize naturally from silicon and the complex compounds formed with iron and aluminum (Kobayashi, 1985). The phenomenon was also reported by Hellawell et al., 1976 and Flood, 1981.

5. Summary and conclusion

The most effective Fe: Co ratio for correcting for iron in Al - 12%Si alloy was found to be 1:1. The optimal tensile strength values for the iron corrected alloys were at their respective maximum removed of iron from the alloys. This showed that the removal of iron improves the general mechanical properties of eutectic aluminum silicon alloy. Among the three iron correctors used (Co, Mn and Mg) Co proved to be most effective as it produced the least strength properties of the studied alloys. However, molebdenum was like cobalt in ductile properties. When the alloys were further modified with sodium, the better and well ordered structures of the silicon produced, resulted to improved mechanical properties. Notwithstanding the above, only slight changes in chemical composition were observed. The improved mechanical properties, particularly the UTS was dependent on the structures and the distribution of the silicon in the eutectic and not necessarily the content in the alloy.

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Plate 1: As cast eutectic Al-Si



Plate 2: Alloy corrected with Mo at ratio Fe: Mo = 2 : 1



Plate 3: Alloy corrected at ratio Fe: Mo = 1:1



Plate 4: Alloy corrected at ratio Fe: Mo = 1:2



Plate: 5 Alloy corrected at ratio Fe: Co = 2:1



Plate: 6: Alloy corrected ratio Fe:Co =1 :1



Plate: 7Alloy corrected at ratio Fe : Co = 1:2



Plate 8: Alloy corrected at ratio Fe: Mn = 2:1



Plate 9: Alloy corrected at ratio Fe: Mn = 1:1

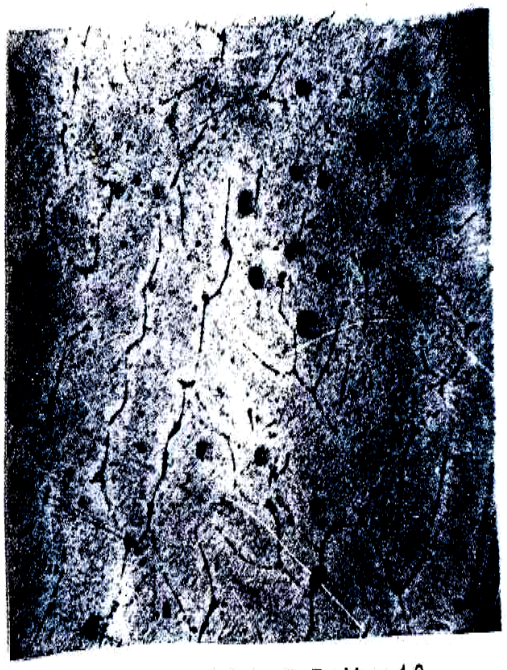

Plate 10: Alloy corrected at ratio Fe: Mn = 1:2



Plate 11: Alloy corrected at ratio Fe: Mo = 1:2



Plate 12: Alloy corrected at ratio Fe: Co=1:1



Plate 13 Alloy corrected at ratio Fe: Mn = 1:2 modified with Na.