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# THE MECHANISM OF IRON REMOVAL FROM Al-Si ALLOYS BY METALLIC DOPANTS AND CONVERSION OF SILICON PLATELETS

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## ABSTRACT

The mechanism of iron removal from Al-Si alloys by dopants was studied with the aim of improving the mechanical and physical properties of the alloys. The mechanism of iron removal from the Al-Si alloys was established with the results obtained from the study. The as-cast Al-Si alloys were analysed for iron content using Atomic Absorption Spectrometer technique. The properties tested were the mechanical (ultimate tensile strength, percentage elongation, microhardness, impact strength and bend test) and physical (electron conductivity and resistivity) properties. Tensile strength was determined using the TUE-C- 100 Model universal tensile machine, impact strength was determined using Samuel Denison, Model LS10 2DE impact testing machine, the bend test by Control Wizard testing machine, Basic Model, microhardness was determined using the Micromet 200 Series Rockwell testing machine Model 60044 and electron conductivity was determined using DDS-307 conductivity meter Model Fs240AA.. The results obtained from the study showed that the ratio of iron to dopant equals to 1:1 gave a decrease of iron from 1.7 to 0.44%. It was found that the formation of iron- rich phases such as $Al_{15}(FeMn)_3Si_2$ and $Al_{15}(FeCo)_4Si_2$ in preference to AlFeSi phases resulted in iron removal from Al-Si alloys. The results also showed a correlation between iron removal and mechanical and physical properties.

***Keywords:*** *Mechanism, Iron removal, Al-Si alloys and Metallic dopants.*

## 1.0 INTRODUCTION

Al-Si alloys contain aluminium, silicon and other impurities from scraps. Solid-state transformations in impure metals are usually limited by the diffusion of the impurities through the bulk of the materials (Michael and Jones, 1994), The most serious problem in Al-Si alloys is the platelet form of solidified Silicon and the presence of brittle iron- containing compounds.

The solidification of Al-Si alloys results in the formation of insoluble iron-intermetallic phases ($Al_8Fe_2Si$, $Al_5FeSi$) and other such structures which are characterised by:

Very high energy of formation that makes the liberation of aluminum contained in them extremely difficult, and

Crystallographic alloy different structure, quite hard, brittle and of sharp melting point (Haizhi,2003).

The Silicon itself crystallizes out in form of platelets with sharp angular edges which act as internal notches or stress raisers, and brittle and soft structures which act as stress concentrators.

Furthermore, iron combines with other elements present in the melt to form other iron-containing compounds, which crystallise on the Si-platelets thus complicating and complexing the stresses.

The second phases (Fe-intermetallics) and solidified Si-platelets are usually hard, coarse and brittle compared with the matrix they are embedded in. Therefore, they can easily break and initiate micro cracks which may propagate and degrade the properties of the Al-Si alloys, especially the ductility. The shapes of the Fe-intermetallics also are detrimental to the properties of the alloys. A sharp second phase for example the needle-like β-$Al_5FeSi$ raises a higher stress concentration and more easily initiates micro cracks (Lifeng and Damoah, 2011). The brittle phase cuts the matrix and produces stress concentration centres that degrade the mechanical properties of the Al-Si alloys.

The Fe-containing intermetallic and solidified Si-platelets obviously are a source of weakness which sharply lowers the mechanical and physical properties and hinders the competitive use of the alloys in jobbing foundries. The iron is known to accumulate during the processing and is difficult to remove (China paper.Com, 2010). Alloying elements principally improve mechanical properties such as tensile strength, hardness and rigidity, Nnuka, Onwu and Nwankwo, (2004)

This study is aimed at improving the tensile strength, relative elongation, impact strength, bend strength, micro hardness and resistivity of the Al-Si alloys by way of brittle milling-down and recompacting of the Si platelets and Fe-intermetallic compounds. The study is important because it helps to effectively utilise aluminium scrap and bequeath more of the cast metal to future generations, Nnuka (1994).

## 2.0 MATERIALS AND METHODS

### 2.1 Materials

The materials and the sources of their procurement, presented in Table 1 were used in sample preparation of the test pieces. Earlier studies in improving the mechanical properties and structure of Al-Si alloys by Nnuka, Agbo and Okeke (2007) and the position of the transition metal in the periodic table of elements served as the basis for selecting doping and modifying elements.

### 2.2 Methods

***Chemical Analysis for Iron Content***

The study specimen, a solid scrap was analysed using the Atomic Absorption Spectrometer (AAS) technique to confirm the iron content. The result obtained from the chemical analysis is presented in Table 2.

***Mould Preparation***

Mild steel mould was used in the preparation of test specimens. The mould of dimension 50 × 60 × 210 mm was cut from a solid block and was drilled centrally from the top to the bottom with a drilling bit of 25mm diameter. It was further drilled down 3mm from the top using 30mm bit to provide enough access into the mould cavity. It was later milled and split into two halves and then guided together into a cylindrical shape. It was then treated with carbon- water solution for protection and easy stripping of castings.

**Table 1. Materials and sources of procurement**

| S/N | MATERIALS | SOURCE | REMARK |
|---|---|---|---|
| 1 | Al-Si | Obtained from Ugo Mechanical Workshop ,Awka | Solid scrap containing 1.7% Fe |
| 2 | Cobalt, Co | Obtained from CIFA Laboratory, Enugu | 96% purity |
| 3 | Manganese, Mn | Obtained from CIFA Laboratory, Enugu | 96% purity |
| 4 | Nickel, Ni | Obtained from CIFA Laboratory, Enugu | 96% purity |
| 5 | Molybdenum, Mo | Obtained from CIFA Laboratory, Enugu | 96% purity |
| 6 | Sodium Chloride, NaCl | Obtained from SEDI, Enugu | |
| 7 | Hydrochloric acid, HCl | Obtained from PRODA, Enugu | |
| 8 | Trioxonitrate(V)acid, $HNO_3$ | Obtained from PRODA , Enugu | |
| 9 | Hydrogen Fluoride, Hf | Obtained from PRODA , Enugu | |
| 10. | Metallic Mould | Obtained from SEDI Enugu | Fabricated from mild steel |

***Charge Preparation***

1000 grams of Al-Si scrap was weighed-out using a chemical balance. The charge was introduced into an electric furnace using metallic crucible and melted at a temperature of 800 $^{o}$C. The melt was doped with 0.85, 1.7, 3.4 and 5.1 % by weight of each dopant (Co, Mn, Mo and Ni) and dissolved by stirring for complete dissolution of the dopants in the melt. The doped and well homogenised melt was cast at a temperature of 720 $^{o}$C and prepared in triplicates for analysis. Measures taken to assure quality of specimens were smearing of the steel mould with water- carbon solution to prevent dissolution of iron in Al-Si alloys, removal of the flux on the surface of the liquid melt and preheating the metallic mould to a preset temperature.

***Tests for Properties***

The studied Al-Si alloys were subjected to mechanical and physical property tests to establish the effects of the dopants on the Al-Si alloys. Standard specimens were cut and prepared and tested using standard methods. Tensile strength was determined using the TUE-C- 100 Model universal tensile machine, impact strength was determined using Samuel Denison, Model LS10 2DE impact testing machine, the bend test by Control Wizard testing machine, Basic Model, microhardness was determined using the Micromet 200 Series Rockwell testing machine Model 60044 and electron conductivity was determined using DDS-307 conductivity meter Model Fs240AA.

Electron conductivity (σ μs/cm) was determined using conductivity meter, Model DDS-307 with Platinum black electrode as the probe medium. Relevant conductivity equation and its transformation as given by Bhargwa (2010) were used to evaluate the electron resistivity.

$\sigma = 1/\rho$, where

σ – Conductivity and

ρ – Resistivity (cm/μs)

Microstructure analysis was performed using a metallurgical microscope "Olympus C-35AD-4" type PMG 3 which was fitted with a camera. Micrographs were observed at magnifications of x100, x200, x500 and x800, while micrographs were taken at x100 magnification and presented in plates 1-5

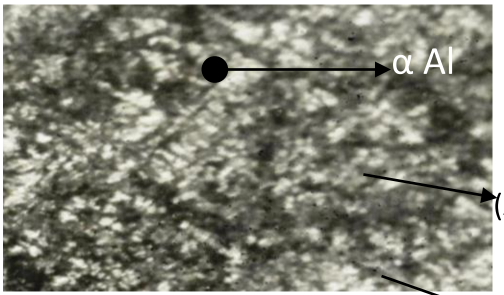


Plate 1: Al-11%Si x100

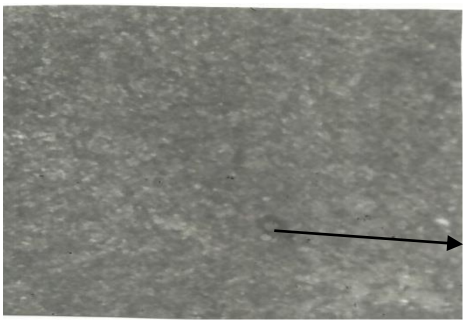


Plate 2: Al-11%Si + 1.7% Co + 1% Na x100

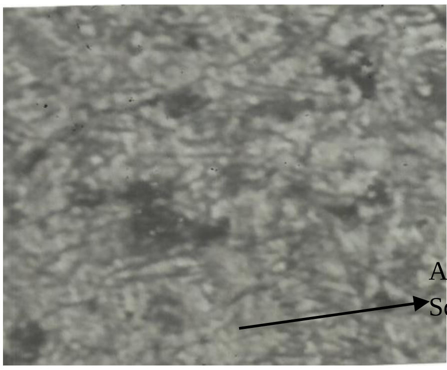


*Plate 3: Al-11%Si + 3.4% Mn + 1% Na 100x*

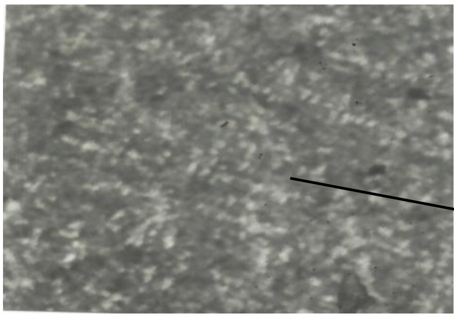


*Plate 4: Al-11%Si + 0.85% Mo + 1% Na 100x*

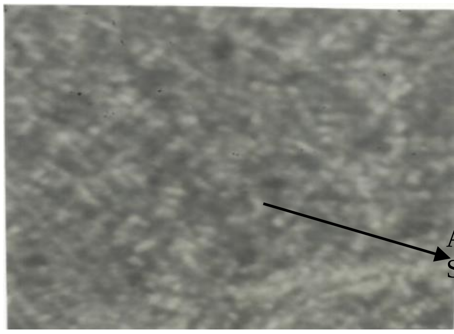


*Plate 5: Al-11%Si + 0.85% Ni + 1% Na 100x*

## 3.0 RESULTS AND DISCUSSION

### 3.1 Results

The results obtained from the investigation are presented in Tables 2 to 5.

**Table2. Chemical analysis of the parent alloy (specimen)**

| Specimen | Element % wt. | | | | |
|---|---|---|---|---|---|
| | Al | Si | Fe | Ca | Other Elements |
| Scrap Aluminum | 82 | 11 | 1.7 | 0,05 | 5.24 |

**Table3. Iron content of the parent and doped Al-11%Si alloys showing quantity of iron removed and the deviation from the critical level.**

| S/N. | Alloy Composition | Iron Content, % | Amount of iron removed, % | Deviation from Fe critical level 0.78%* |
|---|---|---|---|---|
| 1. | Al-Si | 1.70 | 0.00 | + 0.92 |
| 2. | Al-Si + 0.85% Co | 0.43 | 1.27 | - 0.35 |
| 3. | Al-Si + 1.7% Co | 0.44 | 1.26 | - 0.34 |
| 4. | Al-Si + 3.4% Co | 0.31 | 1.39 | - 0.47 |
| 5. | Al-Si + 5.1% Co | 0.33 | 1.37 | - 0.45 |
| 6. | Al-Si + 0.85% Mn | 0.36 | 1.34 | - 0.42 |
| 7. | Al-Si + 1.7% Mn | 0.38 | 1.32 | - 0.40 |
| 8. | Al-Si + 3.4% Mn | 0.48 | 1.22 | - 0.30 |
| 9. | Al-Si + 5.1% Mn | 0.40 | 1.30 | - 0.38 |
| 10. | Al-Si + 0.85% Mo | 0.35 | 1.35 | - 0.43 |
| 11. | Al-Si + 1.7% Mo | 0.19 | 1.51 | - 0.59 |
| 12. | Al-Si + 3.4% Mo | 0.30 | 1.40 | - 0.48 |
| 13. | Al-Si + 5.1% Mo | 0.43 | 1.27 | - 0.35 |
| 14. | Al-Si + 0.85% Ni | 0.12 | 1.58 | - 0.66 |
| 15. | Al-Si + 1.7% Ni | 0.23 | 1.47 | - 0.55 |
| 16. | Al-Si + 3.4% Ni | 0.23 | 1.47 | - 0.55 |
| 17. | Al-Si + 5.1% Ni | 0.39 | 1.31 | - 0.39 |

**Table4. Mechanical and physical properties of Al-11%Si alloys doped with Co, Mn, Mo and Ni.**

| S/N. | Alloy Composition | Mechanical and physical properties | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | UTS $N/mm^2$ | %E | Hv | MOI $J/m^3$ | MOR N/mm | Σ µs/cm | ρ x $10^{-4}$ cm/µs |
| 1. | Al-SI | 124.05 | 0.260 | 236.00 | O.054 | 72.55 | 1880 | 5.32 |
| 2. | Al-Si +0.85%Co | 123.91 | 0.353 | 200.00 | 0.077 | 65.26 | 2840 | 3.52 |
| 3. | Al-Si +1.7%Co | 176.07 | 0.287 | 226.00 | 0.041 | 68.57 | 3910 | 2.56 |
| 4. | Al-Si +3.4%Co | 126.29 | 0.313 | 260.00 | 0.043 | 68.66 | 1840 | 5.43 |
| 5. | Al-Si+5.1%Co | 180.23 | 0.407 | 274.5.0 | 0.027 | 70.56 | 1690 | 5.92 |
| 6. | Al-Si+0.85%Mn | 124.09 | 0.167 | 298.5 | 0.031 | 76.90 | 2020 | 4.95 |
| 7. | Al-Si+1.7%Mn | 124.03 | 0.613 | 167.0 | 0.052 | 55.01 | 1035 | 9.66 |
| 8. | Al-Si+3.4%Mn | 176.27 | 0.320 | 280.5 | 0.064 | 64.25 | 945 | 10.58 |
| 9. | Al-Si+5.1%Mn | 176.03 | 0.227 | 208.0 | 0.050 | 81.16 | 1019 | 9.81 |
| 10. | Al-Si+0.85%Mo | 176.15 | 0.413 | 264.0 | 0.086 | 65.92 | 1580 | 6.33 |
| 11. | Al-Si+1.7%Mo | 176.88 | 0.440 | 285.0 | 0.057 | 75.51 | 1560 | 6.41 |
| 12 | Al-Si+3.4%Mo | 164.62 | 0.347 | 266.0 | 0.068 | 61.60 | 1260 | 7.94 |
| 13. | Al-Si+5.1%Mo | 164.58 | 0.300 | 284.5 | O.052 | 60.28 | 1330 | 7.52 |
| 14. | Al-Si +0.85%Ni | 164.86 | 0.373 | 186.0 | 0.040 | 71.22 | 1050 | 9.52 |
| 15. | Al-Si +1.7%Ni | 160.26 | 0.480 | 180.5 | 0.041 | 56.65 | 1520 | 6.58 |
| 16. | Al-Si +3.4%Ni | 160.30 | 0.247 | 208.5 | 0.057 | 63.94 | 1910 | 5.23 |
| 17. | Al-Si+5.1%Ni | 156.17 | 0.333 | 217.0 | 0.027 | 67.97 | 2060 | 4.86 |

**Table5 Physical and mechanical properties of Al-Si and maximally improved Al-Si alloy.**

| S/N | Alloy composition | Mechanical properties | | | | | Physical properties | |
|---|---|---|---|---|---|---|---|---|
| | | UTS $N/mm^2$ | $\%Ex10^{-1}$ | Hv | MOI $J/cm^3$ | MOR N/mm | Σ µs/cm | ρ x $10^{-4cm/\mu s}$ |
| 1. | Al- Si | 124.05 | 2.60 | 236.0 | 0.054 | 72.55 | 1880 | 5.32 |
| 18. | Al-Si+1.7%Co+1%Na | 148.29 | 5.47 | 231.0 | 0.072 | 51.61 | 1054 | 9.49 |

### 3.2 Discussion

Table 3 shows the iron content of the doped alloys as-cast and of the parent alloy (Al-11%Si). In all the studied alloys, removal of iron occurred which was attributed to the action of the doping elements and the entry into sludge. The amount of iron removed increased from 74 to 93%. The role of dopants in the removal of iron from Al-Si alloys can be explained as follows;

The iron impurity in Al-Si alloys ties up the Si and Al as insoluble AlFeSi crystallites which reduce the fluidity and the amount of aluminum in the eutectic Al-Si alloys. At the processing temperature and time, the solubility of iron in aluminum is high and as the temperature falls, the solubility of the iron also decreases. The iron that precipitates out of the alloy due to its higher affinity for dopants and low solid solubility of iron, forms Fe-rich phases such as $Al_{15}(FeMn)_3Si_2$ and $Al_{15}(FeCo)_4Si_2$. The phase/s ($Al_{15}(FeMn)_3Si_2$ and other iron-rich intermetallic compounds formed) are compacted into blocky form due to the action and physics of the dopants in comparison with the needle-like α and β(AlFeSi) intermetallic structures that degraded the alloys.

The role of dopants in the formation of Fe-rich phase can be explained in terms of strong metallic bond between the atoms of the dopants and iron as a result of their similarity in properties. This has been reported by Khurmi and Sedha, (2004).

Analysis of Table 4 shows that the improvement of strength was favoured by the removal of iron below the iron critical level through the process of doping at the holding time and processing temperature. The well doped Al-Si alloys were at the peak tensile strength after the removal of iron from the melt. This agrees with the report of Henkel and Pense (2002) that the reduction in both strength and ductility is caused by an increasing amount of AlFeSi crystallites in place of the fine eutectiferous silicon. This was also confirmed by the micrographs of maximal doped and sodium modified Al-Si alloys (plates 2-5). No primary alpha intermetallic compounds were observed while the Si becomes finer in comparison to the parent alloy (plate 1), This can be explained by the quantity of iron removed and consequent modification and refinement of the structure by sodium chloride

## 4.0 CONCLUSION AND RECOMMENDATION

The following conclusions were made from the results and the micrographs obtained from the investigation.

1. Iron removal from Al-Si alloys by dopants is feasible and a mechanism of iron removal was established based on the formation of iron enriched phase and the sludge.
2. The percentage of iron removal with maximal Co dope was 74% and the deviation of the removed iron from the critical iron level was (–0.34).
3. The removal of iron from Al-Si alloys favoured the enhancement of its mechanical properties. The improvement was made manifest when the doped and modified alloys were compared with the initial aluminium alloy.
4. The effectiveness of the dopants as Fe-removing agents for Al-Si alloys was found to depend on the concentration of the elements. This was confirmed by the effects of the variation of the composition of the dopants.
5. The conversion of the silicon platelets to a regular form by Na raised the ductility further producing a tougher metal which can be bent easily.

6. The improved alloys are recommended for shaped castings of machine and engine parts, ingots as well as fibre reinforcement for plastics.

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