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Effect of IRON Removal on the Structure and Mecahnical Properties of Aluminium-Silicon Alloys

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ABSTRACT

The research work examined the effect of the removal of iron from aluminium-silicon alloys using dopants on the structure and mechanical properties. Manganese, cobalt and molybdenum were used as the modifying elements. The as-cast Al - Si alloys were analyzed for iron content using Atomic Absorption Spectrometer (AAS) technique. The dopants or modifying elements were added as micro additives at various compositions to the percentage of iron present in the master alloys. The modified alloys were produced by melting a calculated mass of the master alloys and adding the dopants in the ratios of 1:1, 2:1, 3:1 and 4.1 to the percentage of iron in the Al - Si alloy. The properties tested were ultimate tensile strength, percentage elongation, hardness and microstructure. The result of the chemical analysis of the alloys indicated that the dopants were able to reduce the percentage of iron in the alloys. On addition of 5.4%Co iron was reduced from 1.8% to 0.42%, which is far less than the critical iron level of 0.78%. The mechanical tests showed an improvement with the highest values achieved by the addition of 5.4%Co. The improvement in the microstructure is also shown in plates 1-8.
Keywords: Micro Additives; Microstructure; Hardness; Strength; Composition

I. INTRODUCTION

Castings are the main use of aluminium - silicon alloys, although some sheets or wires are made for welding and brazing. Magnesium and manganese when added to Al - 12% Si alloy improve the strength, fluidity and resistance to corrosion [12]. An improved fluidity enhances the surface finish of castings [6]. Aluminium - Silicon alloys are the most commonly used alloys in the automotive, defence and aerospace industries mainly because of their high strength to weight ratios, better castability and good surface finish [11]. They also present good wear resistance and high welding characteristics. These alloys are also less prone to shrinkage, hot cracking and porosity defects when compared to other aluminium casting alloys such as Al-Cu alloys. Structural components made from aluminium and its alloys are vital to the areas of transportation and structural materials [1].

Aluminium in its pure state is a soft metal with low tensile strength. Substantial increase in strength can be obtain by alloying and cold working, but higher strength as demanded in various engineering applications can be obtained by suitable alloying elements to impart high fluidity and low shrinkage, necessary for good castings [2]. Eutectic alloy composition of Al-12.5%, Si is widely used for casting because of its high fluidity and castability. Iron is the main impurity in eutectic aluminium silicon alloy and efforts should be made to keep it as low as tolerable and economically possible because of its deleterious effect on strength, ductility and corrosion resistance. Structural modification can be achieved using various additives. It is known that cobalt, manganese, nickel, chromium, molybdenium, sodium chloride, sodium fluoride, e.t.c. had been used to modify the structure and properties of Al-Si alloys [8,10]. In general, the addition of grain refiners increases the number of grain nucleation sites and reduces grin size. It has been know that in aluminium alloys the grain size alone does not define the mechanical properties. Other factors that contribute to the eventual definition of the mechanical properties are the dendrite size of the metallic base, the distribution of the alloying elements, changes in the distribution pattern and the form of the eutectic precipitates [9,3,13].

Although iron is highly soluble in liquid aluminium and its alloys, it has very little solubility in the solid, and so it tends to combine with other elements to form intermetallic phase particles of various types [5]. In the absence of Si the dominant phases that form are Al3Fe and Al6Fe, but when Si is present, the dominant phases are Al8Fe2Si (α - alpha phase) and Al5FeSi (β - beta phase). If Mg is also present with Si, an alternative phase, Al8FeMg3Si6 called p - pi phase can form. Another common phase that forms when Mn is present with Si is Al15 (Fe.Mn)3Si2, is also confusingly known as α - alpha phase. This phase tends to form in preference to the other α-alpha phase [14]. The Al-Si alloy usually has some other co-existing elements such as copper, magnesium, manganese, zinc and iron. The solubility of these elements in aluminium usually increases with increasing temperature. This decreases from high concentration at elevated temperatures to relatively low concentrations during solidification and heat-treatment, resulting in the formation of secondary intermetallic phases. For instance, the precipitation of Si, Mn and Fe forms an Al12(Fe.Mn)3Si phase. The wide variety of inter metallic phases in aluminium alloys occur because aluminium is highly electronegative and trivalent [7].

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 Al-Si alloys, especially the ductility. A sharp second phase for example the needle-like Al5FeSi raises a higher stress concentration and most often easily initiates micro-cracks [5]. The Fe-containing intermetallics and solidified Si-platelets obviously are source of weakness which sharply lower the mechanical and physical properties and hinder the competitive use of the alloy in foundry industries.

The study is aimed at improving the tensile strength, relative elongation, impact strength, hardness and micro-hardness of the eutectic Al-Si alloys by reducing the formation of Fe-intermetallic compounds and modifying the platelets. The study is important because it will help to increase the utilization of eutectic aluminimum-silicon alloys castings for automotive, aircraft, automobile spare parts, ship building industries e.t.c.

II. METHODS AND MATERIAL

The following materials and equipment were used in this research work. They include: pure aluminium ingot, silicon powder, cobalt, manganese, molybdenium, moulding sand, moulding boxes, metallic patterns, crucible furnace (oil fired), crucible pot, pouring cup, scooping spoon, hack saw, weighing balance (digital), bench vices, lathe machine, Vickers hardness tester, universal tensile testing machine, metallurgical microscope with camera attachment, Atomic Absorption Spectrometer (AAS), e.t.c. Weight percent was used in the charge calculation of the raw materials and measured using digital weighing balance. The furnace and crucible port were thoroughly cleaned and preheated before charging. Aluminium was first charged into the furnace heated to molten stage before introduction of silicon. Constant stirring was carried out to ensure a homogenous mix. When the melting was completed, the molten metal was cast and allowed to solidify to room temperature. After removal of the cast from the mould, the chemical composition of the alloy was analyzed using Atomic Absorption Spectrometer (AAS). The iron content of the produced alloy was found to be 1.8% as presented in Table 1. The samples requiring modification were cut off from the main stock and weighed. The appropriate weight percentages in the ratio 1:1, 2:1, 3:1 and 4:1 of the modifying elements to iron were calculated, weighed and their charges prepared accordingly, melt and cast into cylindrical shapes as specimens.

The specimens including the unmodified sample were machined to specification (ASTM), internationally accepted standard for various mechanical tests. The tests carried out include; tensile (ultimate tensile strength), percentage elongation, impact strength and hardness. The specimens, for microstructural examination were ground using emery papers (silicon carbide papers) in the order of 220, 320, 400, 600, 800, 1000 and 1200 grits respectively. They were then polished using alumina (Al_2O_3) and etched. The structures of the etched specimens were viewed in a metallurgical microscope and the photomicrographs taken using a digital camera.

III. RESULTS AND DISCUSSION

Table 1: Chemical composition of the parent alloy (Eutectic aluminium-silicon alloy)

Element	Al	Si	Fe	Ca	Mg	Others
Wt %	85.40	12.45	1.80	0.05	0.15	0.15

The result of the chemical composition of the produced eutectic aluminium-silicon alloy is shown in Table 1. The result indicated that the iron (Fe) content of the alloy is 1.8%, which is far higher than the accepted critical level of 0.78%. This is an indication that if the alloy is used without reduction of its iron content, the alloy will probably experience deterioration in service due to its susceptibility to development of micro-cracks and corrosion attack. This hinders the competitive use of this alloy in foundry and automotive industries.

Table 2: Aluminium-silicon, aluminium-silicon with modifying elements and quantity of iron removed.

Sample description	Alloy composition	Iron (Fe) content	Amount of Iron (Fe) removed	% of iron removed	Deviation from the critical Fe level, 0.78
A	Al - Si	1.80	0	0.00	+ 1.02
B	Al-Si + 1.8% Mn	1.10	0.70	38.88	+ 0.32
C	Al-Si + 3.6% Mn	0.90	0.90	50.00	+ 0.12
D	Al-Si + 5.4% Mn	0.70	1.10	61.11	- 0.08
E	Al-Si + 7.2% Mn	0.70	1.10	61.11	- 0.08
F	Al-Si + 1.8% Co	0.54	1.26	70.00	- 0.24
G	Al-Si + 3.6% Co	0.48	1.32	73.33	- 0.30
H	Al-Si + 5.4% Co	0.42	1.38	76.67	- 0.36
I	Al-Si + 7.2% Co	0.45	1.35	75.00	- 0.33
J	Al-Si + 1.8% Mo	1.20	0.60	33.33	+ 0.42
K	Al-Si + 3.6% Mo	1.50	0.75	41.67	+ 0.27
L	Al-Si + 5.4% Mo	0.85	0.95	52.78	+ 0.07
M	Al-Si + 7.2% Mo	0.75	1.05	58.33	+ 0.03

Table 2, shows the iron content of the eutectic aluminium-silicon alloy, the quantities removed by the addition of dopant elements and the deviation from the acceptable critical iron level. From the Table, it could be observed that cobalt has more pronounced effect on the iron removal from Al-Si alloy. At a ratio of 3:1, about 76% of iron was removed by cobalt. At the same ratio, manganese was able to remove only about 61% of iron, while molybdenium removed about 52%. Manganese, iron and cobalt are in the same Period (Period 4) in the Periodic Table of Elements in an increasing atomic number. Cobalt has smaller atomic radii than iron and hence was able to enter interstices and displace iron radii in intermetallic compound/phase of AlFeSi while manganese with larger atomic radii has less effect on iron removal. Molybdenium had lesser effect than cobalt and manganese because it is in Period 5 and required more energy for it to be able to displace iron. Therefore, cobalt displaces iron more easily from iron-aluminium-silicon intermetallics phase by forming more nucleation sites which induces grain refinement and hence higher strength.

In all the studied alloys, the possibility of iron removal was attributed to the action of the dopants on iron on their entry into molten eutectic aluminium-silicon alloys. The amount of iron removed increased from 33% for iron: molybdenium ratio of 1:1, to 76% for colbalt: iron ratio of 3:1; see Table 2 and Figure 1. The iron impurity in Al-Si alloys ties up silicon and aluminium as insoluble AlFeSi crystallites which reduce fluidity and amount of aluminium in the eutectic alloy. At the processing temperature and time, the solubility of iron in aluminium is high but as the temperature falls, the solubility decreases. The iron which precipitates out from the alloy due to higher affinity for the dopant elements form Fe-rich phases such as Al15(FeMn)3Si2 and Al15(FeCo)4Si2. The phases [Al15(FeMn)3Si2 and other iron rich intermetallic compounds] formed are compacted into block form due to the action and physics of the dopants in comparison with the needle-like α and ρ. AlFeSi intermetallic structure that degrade the properties of the alloys. See the micrographs, Plates 1-8.

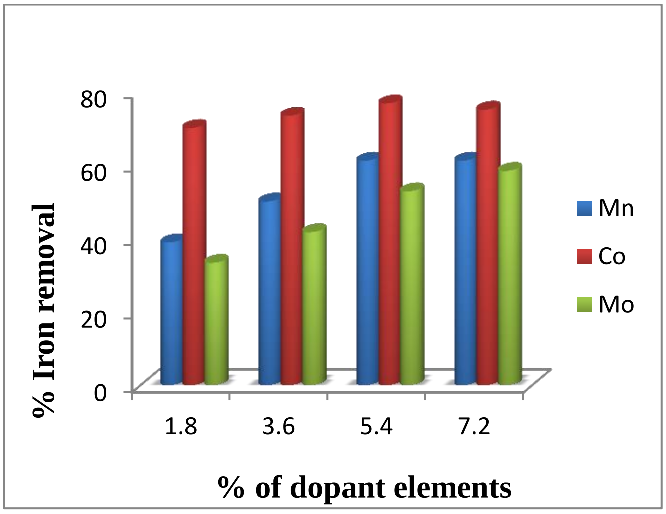

Figure 1: Relationship between dopant elements and quantity of iron removed

Table 3: Results of mechanical tests

Samples	Ultimate tensile strength UTS (N/mm^2)	% Elongation	Impact energy (J)	Hardness VHN	% Iron (Fe) content
A	225	8.7	1.5	206	1.80
B	229	9.5	1.6	209	1.10
C	234	10.7	1.5	217	0.90
D	236	11.4	1.6	217	0.70
E	240	11.9	1.7	214	0.70
F	249	10.6	1.5	216	o.54
G	253	11.5	1.6	221	0.48
H	258	12.3	1.65	226	0.42
I	252	12.0	1.8	219	0.45
J	227	9.4	1.5	207	1.20
K	230	9.9	1.6	213	1.05
L	233	10.8	1.6	220	0.85
M	231	11.3	1.52	217	0.75

From Table 3, it could be seen that the mechanical properties tested; tensile strength, hardness and impact energy increased progressively with increase in the ratio of the dopants to the iron content in the alloy. The higher the quantity of iron removed, the higher the mechanical properties. The mechanical properties, hardness and tensile strength declined after a pick of ratio 3:1, for all the elements used (see Figures 2 and 3). This is an indication that after this ratio, the solubility of these elements in Al-Si alloy reduces (see Table 3 and Figure 1-4. The well modified Al-Si as could be seen in the master alloys were at the peak of tensile strength after reduction of iron from the melt by the dopants. This agrees with the report [4] that stated that the reduction in both strength and ductility is caused by an increasing amount of AlFeSi crystallites in place of fine eutectiferous silicon.

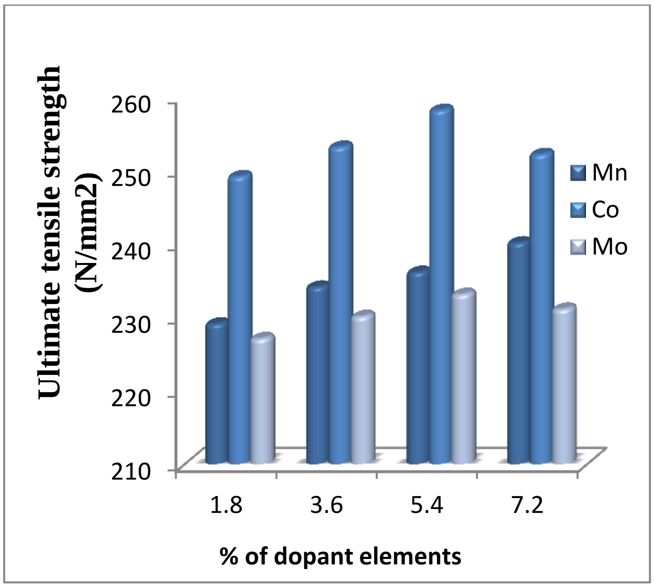

Figure 2: Effect of dopants on the ultimate tensile strength of Al-Si alloys

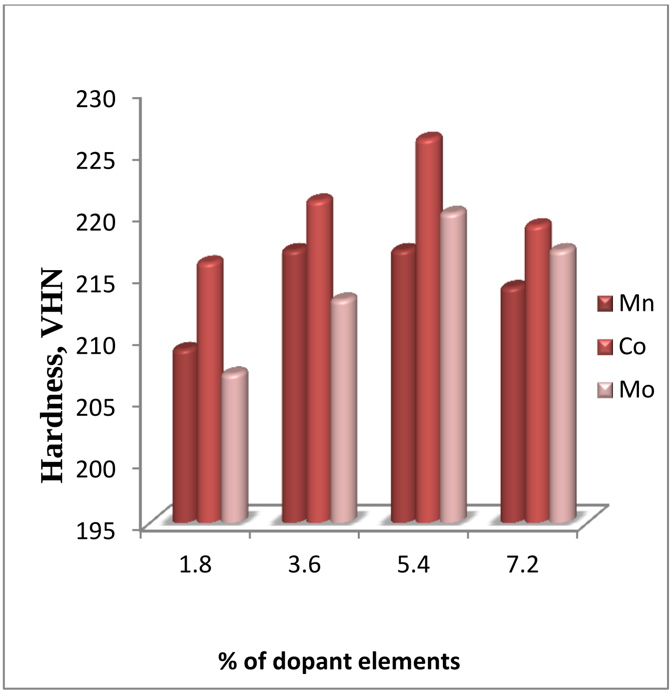

Figure 3: Effect of dopants on the hardness of Al-Si alloys

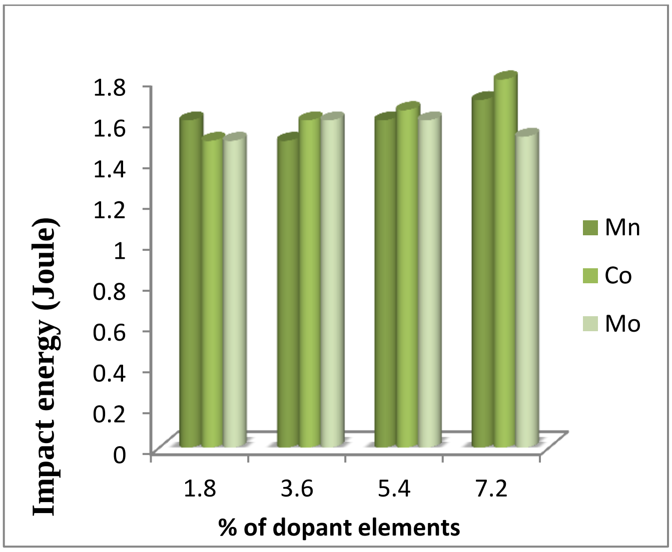

Figure 4: Effect of dopants on the impact energy of Al-Si alloys

IV. CONCLUSION

The following conclusions were made from the results of the mechanical tests and micrographs obtained from the alloys studied.

a. Iron removal from Al-Si alloys by dopants is feasible and a mechanism for this established based on the formation of iron-enriched phases.
b. The highest percentage of iron removal of 76% was obtained for iron: cobalt ratio of 1:3 and the

deviation of the removed iron from the critical iron level in Al-Si alloy was, -0.36.

c. The removal of iron from Al-Si favoured improvement of its mechanical properties. The improvement was made manifest when the doped alloys were compared with the parent Al-Si alloy.
d. The effectiveness of the dopants as iron removing agents for Al-Si alloys was found to depend on the concentration of the dopants.
e. The conversion of the silicon platelets or needle like structures into block form raised the tensile strength, ductility and impact energy i.e toughness hence producing an alloy with improved bend strength and malleability.
f. The improved alloys are recommended for use in foundry works for the production of shaped machine parts and engine reinforcement.

V. ACKNOWLEDGEMENT

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Micrographs of the studied specimens (x 400)

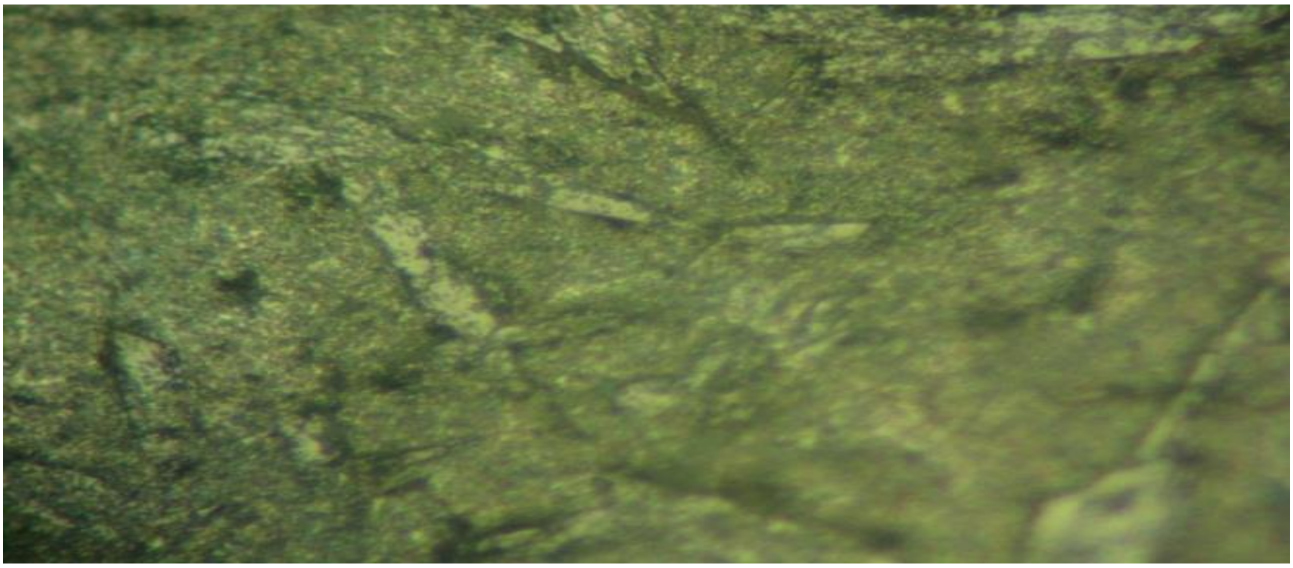

Plate 1: Micrograph of Al-Si alloy (as-cast)

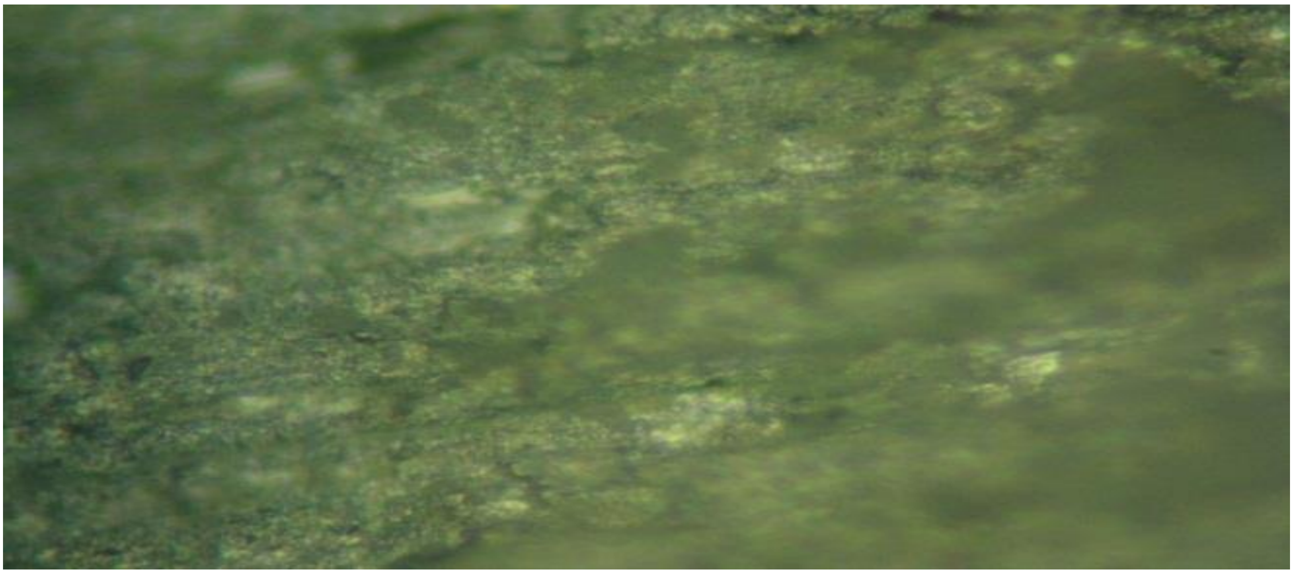

Plate 2: Micrograph of Al-Si-1.8%Mn alloy

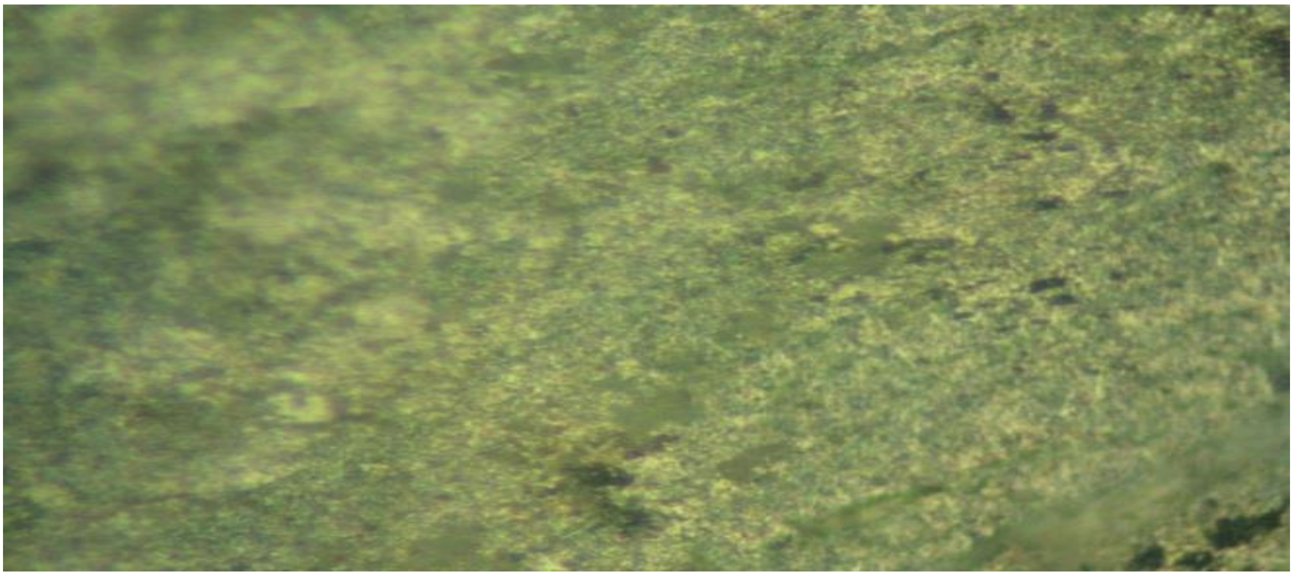

Plate 3: Micrograph of Al-Si-3.6%Mn alloy

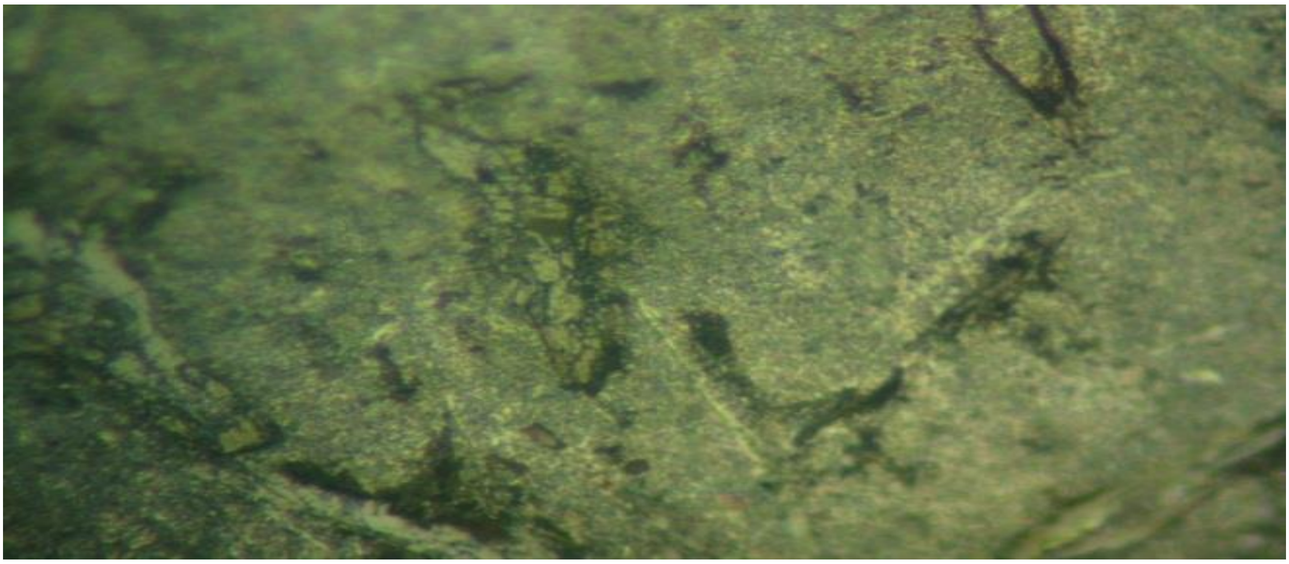

Plate 4: Micrograph of Al-Si-1.8%Co alloy

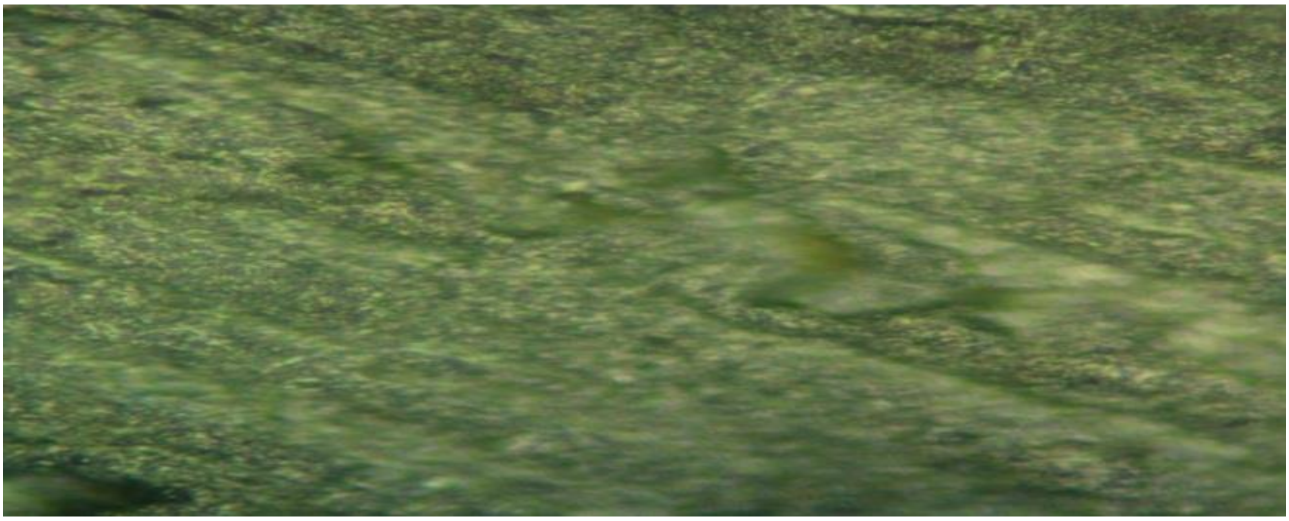

Plate 5: Micrograph of Al-Si-3.6%Co alloy

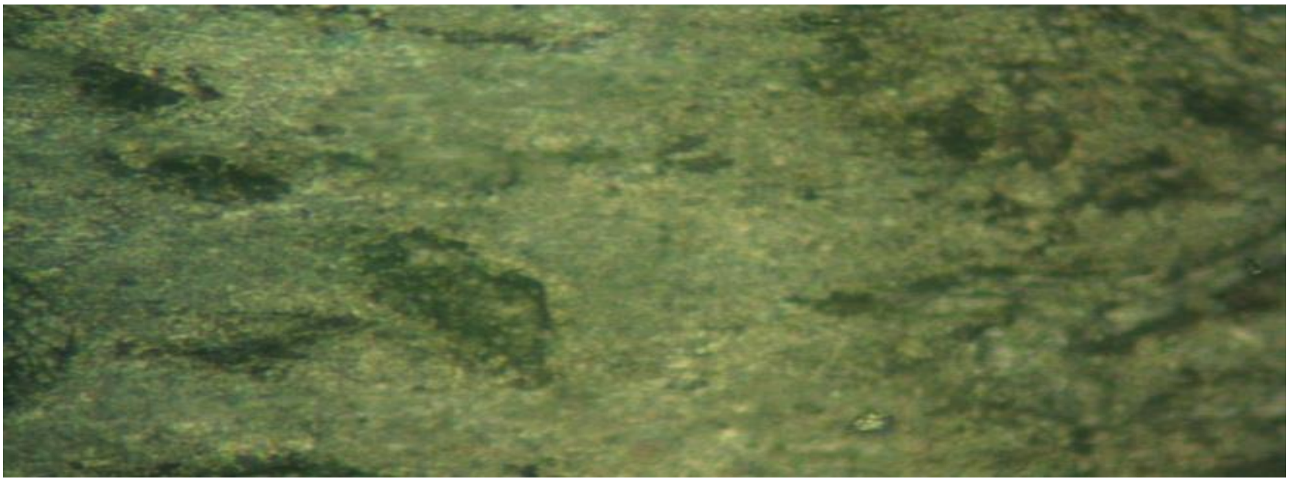

Plate 6: Micrograph of Al-Si-1.8%Mo alloy

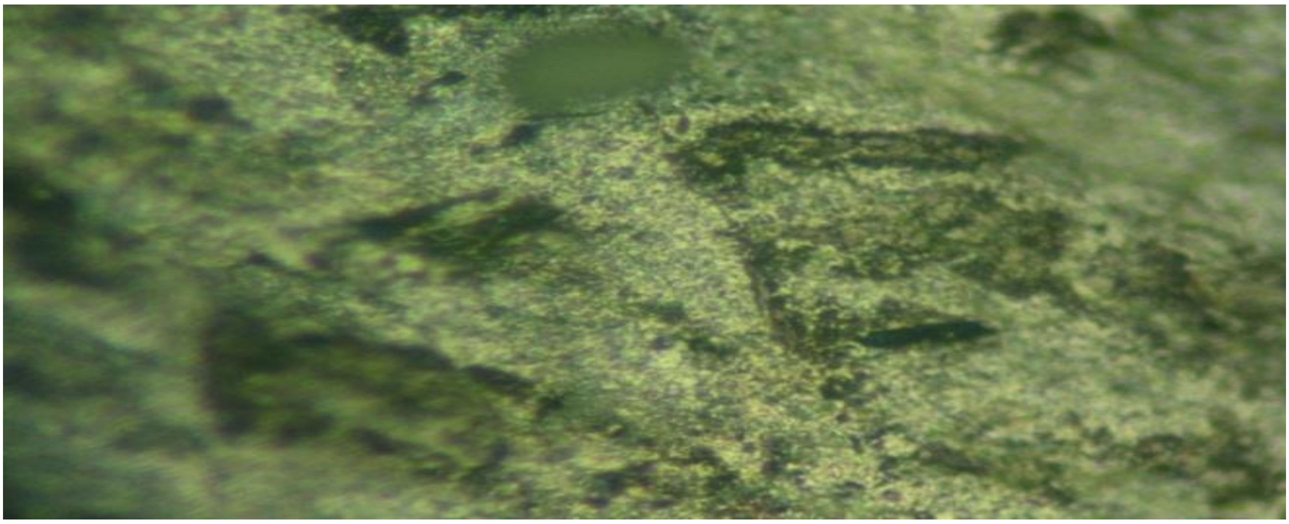

Plate 7: Micrograph of Al-Si- 3.6%Mo alloy

Plate 8: Micrograph of Al-Si-7.2%Mo alloy