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Research Article

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Effects of Chromium and Molybdenum on the Structure and Mechanical Properties of Al-Si Alloys obtained by Metal-Mould Casting

Onyebueke B Ifeanyi, Nwankwo E Nkem, Anene F Amaechi

Metallurgical and Materials Engineering Department, Nnamdi Azikiwe University, Awka, Nigeria

Abstract The effects of Cr and Mo was investigated on the structure and mechanical properties of Al-12%Si alloys. Alloys of Al-12%SixCr and Al-12%SixMo were prepared by melting in a controlled crucible furnace of graphite pot. Fully molten Al formed was properly mixed with a specified weight of alloying elements (Si, Cr and M_o), cast and solidified in metal mould of standard dimension. Hardness and tensile strength of specimens were determined using Brinell hardness Tester and Monsanto Tensometer respectively whereas the microstructure examination was conducted using an Optical Microscope. The results obtained from the experiments show that the tensile strength and hardness of the maximum improved Al-12%Si alloy increase from 21.31 N/m^2 to 74.16 N/m^2 and from 84.9 HB to 245 HB respectively. Optical microscopy reveals the distribution of elements in the structure of both unmodified and modified Al-Si alloys. The results of the experiments are explained in terms of the vastly improved grain structures resulting from the presence of solute atoms in the modified Al-12%Si alloys and the large undercooled change observed in Al-Si melt.

Keywords Mechanical, Metal-mould, Al-Si alloy, Structure Casting

Introduction

Al and its alloys have been identified as an important and useful engineering material. It is attracted by its various unique properties; such as appearance, strength to weight ratio, excellent thermal properties, workability properties and good mechanical behavior [1].

In recent years, Al alloys are widely employed in the automobile industry. This is particularly due to the need to reduce weight which is geared towards conforming to the green energy regulations as regards fuel consumption and efficiency. Cu, Mg, Mn, Si and Zn are typical alloying elements that are regularly used to improve or alter the properties of pure Al. Al alloys of different configurations containing major elemental additives of Mg and Si are now being used to replace steel panels in various automobile industries. Deformation of lattice caused by the difference in diameter of Al and Si atoms make the dislocation movement difficult. This is caused by very strong interaction between either screw and edge dislocation and the stress field introduced by the substitution atoms [2].

Of all the various Al alloys that are in use today, the one that is in greater use is the Al-Si alloy. It is considered as the most cast friendly Al alloy. The eutectic composition of Al-Si alloy is at a composition of about 12% Si and is the most widely used for casting because of its high fluidity and castability [3].

It is known that Co, Mn, Mo, Ni, NaCl alongside NaF had been used to improve the structure and modify the brittle Si platelets in Al-Si alloys [4]. In addition to chemical composition, the structure and mechanical properties of alloys depend on many factors that act during solidification. Important factors are the structure of the melt, the crystallization rate, and the temperature gradient at the liquid–solid interface [5]. Co, Cr, Mn, Mo and Ni are sometimes added as correctives for iron; their addition also improves strength at high temperature. Cu is added to increase the strength and fatigue resistance without loss of castability, but at the expense of corrosion resistance. Mg, especially after heat treatment, increases substantially the strength, but at the expense of ductility [6].

It has been stated [7] that the addition of Cr as a modifier to the Al-Si alloy suppresses the grain growth at elevated temperatures. Also, it improves the ductility and toughness of Al containing Si and alloy because of the modification of Al_5FeSi intermetallic inclusions from platelet to cubic form. He also noted that Cr modification reduces the susceptibility of the alloy to stress corrosion cracking.

At the higher temperatures elements with high melting points (Ni, Co, Cr, and Mo) reduce to some extent the decline in strength, although their effect is not substantial. Be, too, is reported to improve the high-temperature strength. The effect of the strengthening of Al solid solution by the of atoms of smaller radii than Al (such as Mn, Fe, and Cu) is more evident than in the case of atoms of larger radii(such as Mg), this is because , when the solute atoms are less than the solvent atoms, localized stress field are created. Depending on their relative locations, solute atoms will either attract or repel dislocation in their vicinity. This is known as the size effect. This allows the solute atoms to relieve either tensile or compressive strain in the lattice, which in turns puts the dislocation in a lower energy state. In substitution solid solutions, these stress fields are spherically symmetric, meaning that they have no shear stress component. As such, substitutional solute atoms do not interact with the shear fields characteristics of screw dislocations. Conversely, in interstitial solid solutions, solute atoms cause a tetragonal distortion, generating a shear field that can interact with the edge, screw, and mixed dislocations. The attraction or repulsion of the dislocation centers to the solute particles increase the stress it takes to propagate the dislocation in any other direction. Increasing the applied stress to move the dislocation increases the yield strength of the material [8]. The yield strength of pure Al is 7-11Mpa, while alloys have yield strengths ranging from 200Mpa to 600Mpa.

Materials with great strength offer high load carrying capacity whereas good ductility prevents sudden and catastrophic failure of engineering materials. However, good strength and ductility are very much incompatible. And any attempt to improve any of them, jeopardizes the other [9].

Although Si is a good alloying element for Al, the resulting Al-Si alloy still lacks high mechanical properties which are required for many engineering applications. This goes a long way to limit its use for engineering applications. Binary Al-Si alloys in the unmodified state, near to the eutectic composition exhibit acicular or lamellar eutectic Si which is in the form of large plates with sharp sides and edges. Al-Si alloys containing more than 12% Si exhibit a hypereutectic microstructure normally containing primarily Si phase in a eutectic matrix. Cast eutectic alloys with coarse acicular Si show low strength and ductility because of the coarse plate-like nature of the Si phase that leads to premature crack initiation and fracture in tension. Similarly, the primary Si in normal hypereutectic alloys is usually very coarse and imparts poor properties to these alloys. Therefore, alloys with a predominantly eutectic structure must be modified to ensure adequate mechanical strength and ductility [13].

The project aims to significantly improve the mechanical properties of Al-Si alloys through the control of the microstructure by Cr and Mo additions, with the objective to establish the effects of Cr and Mo on the mechanical properties of Al-Si alloy, the metal and content between the two dopants that impacts the maximum hardness and tensile strength on an Al-12%Si alloy.

Materials and Methods

The sequence of operations followed to obtain the studied specimens and the mechanical test results include.

The use of calculated quantities of virgin Al ingots, Si, Cr and Mo powders. The materials were weighed out in their appropriate proportion respectively using a weighing balance.

Mould preparation for casting the alloy samples involved cleaning the mould surfaces with a wire brush and spraying the cleaned surfaces with dycote ($CaCO_3$) for easy removal of casting after which the mould is coupled and made ready for casting. The mould is designed to completely solidify and form appropriate grain structure required for tests and to allow for ease of handling

The furnace used for sample preparation is a crucible furnace with a graphite pot of maximum controlled temperature of about 1750°C. Prior to charging of metal into the furnace, the crucible pot is removed and properly cleaned to avoid contamination by other material inclusions.

Melting and Casting of Sample Alloys

A binary Al-12%Si alloy and other Al-12%Si-based alloy series of compositions Al-12%SixMo and Al-12%SixCr (xMo and xCr contents of 0.55 to 5.00 %wt and in ratio with both Al and Si) were melted using a preheated crucible pot. At every heat of the melts, the crucible with its content was introduced into the furnace. Temperature control of the furnace was carefully done through regulatory nobs of the furnace to prevent overheating.

The Al ingots were charged into the preheated crucible furnace and superheated above its melting point, the liquid metal formed was properly and carefully mixed with specified weight of each alloying elements (Si, Cr and M_o) in the ladle and was quickly cast into a well prepared metal mould and solidified by gravity only.

Microstructure Examination

The microstructure examination was done by metallographic techniques in order both to reveal the microstructural details of the sectioned specimens of Al-Si alloy as-cast and also to show the changes that occurred in the microstructure due to the definite presence of Mo and Cr elements. This was carried out with the aid of a Computer -Optical Microscope (C-OM).

In the process, a cubic sample was cut out from each of the five cast samples. The samples were ground with emery paper of different grits with decreasing coarseness from 220, 400, 600, 800, 1000 and 1200 grades. The samples were held in such a way that each successive grinding was done at right angle to the previous one and periodically rinsed in running water to prevent overheating and thermal damage of the samples. The next operation was polishing using the polishing machine until a mirror like surface was obtained for each specimen. The specimens were then washed thoroughly and dried using the oven dryer.

After drying, the specimen were inserted into dilute hydrofluoric acid which was the etching reagent, for about 10-15 seconds and the layers of the specimens were attacked chemically until the polished surface were slightly discolored or dull in appearance. The etched specimens were washed in water to stop the etching action. The specimens were dried and viewed under a high powered electron microscope with a magnification of x400 for micro structure analysis and micrographs showing the different morphologies of Al, Si etc were taken.

Hardness Test

The test was conducted using a Brinell testing machine model HBS 5/250/30. Below the control panel of the brinell testing machine are, a microscopiclens, digital camera and indenter which are connected to each other and rotates toward the work piece as required.

The specimen each of 20 mm in diameter were polished, placed on an adjusting table below the control panel separately, the table was raised to the focus of the microscope which helped to determine the exact spot for indentation.

On pushing the start button on, the microscope returned automatically to its resting position and the spherical indenter was carefully placed on the specimen surface. A specified force was applied and maintained for about 15 seconds after which the indenter bounced back to its formal position.

The indentation was clearly seen on the monitor of the Brinell testing machine, the diameter of the indentation was obtained by placing four metric lines on the edges of the indentation using hand control knob. The diameter obtained and the force applied were used by the machine to calculate the brinell hardness of the workpiece. Brinell hardness result was displayed on the bottom left hand corner of the monitor. Three (3) indentations were taken on each specimen and the mean was obtained.

Tensile Test.

The tensile test was conducted using a Hounsfied Universal Monsanto Tensometer Machine (ASTM-D 790-99).

Specimens for this test where machined to a dumbbell shape which is the required standard specification so as to fit the grips, as showed in the figure above. The testing process started with the specimen labeled 1 and continued on to 11. The specimens were placed each between the two grips, these held the specimen in place, gradual force is applied on the work piece till it fractured. Different values of force and extension were obtained and reported.

Results and Discussions

The hardness test, micro-structural examination, percentage elongation and tensile strength tests were carried out on the test specimens each representing a different cast of Al-12%Si alloys modified with different Mo and Cr contents. The results obtained from the property tests are presented in tables 1 and 2, and the micrographs showing remarkable changes in morphologies in plates 1 to 5.

Table 1: Brinell Hardness of Al-12%Si alloys.

SN	Alloy composition	Loading time (sec)	Load used (Kg)	Hardness (HB)
1	Al-12%Si	15	250	84.9
2	Al-12%Si0.55%M_o	15	250	103.7
	Al-12%Si0.82%M_o	15	250	110.5
4	Al-12%Si1.64%M_o	15	250	178.9
5	Al-12%Si3.30%M_o	15	250	142.3
6	Al-12%Si5.00%M_o	15	250	238.3
7	Al-12%Si0.55%Cr	15	250	104.2
8	Al-12%Si0.82%Cr	15	250	107.0
9	Al-12%Si1.64%Cr	15	250	182.0
10	Al-12%Si3.30%Cr	15	250	179.0
11	Al-12%Si5.00%Cr	15	250	245.6

Table 2: Tensile Strength of Al-12%Si alloys

S/N	Alloy Compositions	Breaking force (N)	% elongation	UTS (N/m^2)
1	Al-12% Si	1072	3.13	21.31
2	Al-12% Si0.55%M_o	1300	2.68	25.84
3	Al-12% Si0.82%M_o	2795	2.35	55.57
4	Al-12% Si1.64%M_o	2880	1.50	57.26
5	Al-12% Si3.30%M_o	2540	0.95	50.50
6	Al-12% Si5.00%M_o	3590	0.41	71.30
	Al-12% Si0.55%Cr	1277	2.48	25.39
8	Al-12% Si0.82%Cr	2640	2.24	52.49
9	Al-12% Si1.64%Cr	2609	1.20	49.90
10	Al-12% Si3.30%Cr	2783	1.05	55.33
11	Al-12% Si5.00%Cr	3730	0.57	74.16

Plate 1: Micrograph of Al-12%Si alloy as-cast.

Plate 2: Micrograph of Al-12%Si with 5%Mo.

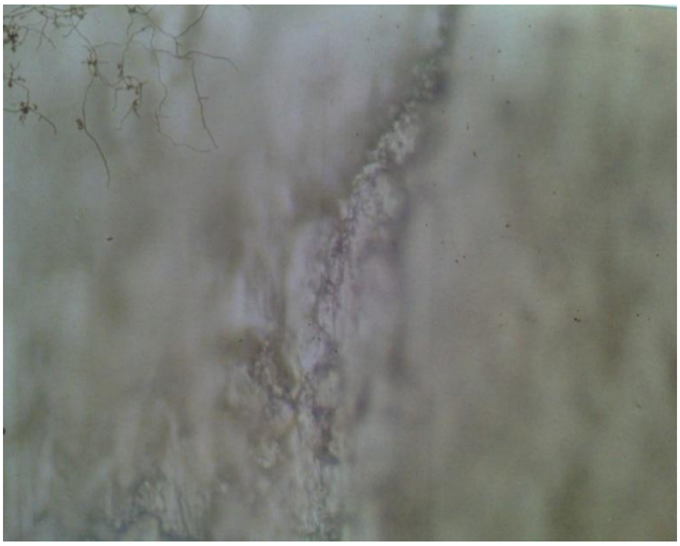

Plate 3: Micrograph of Al-12%Si with 5%Cr.

Plate 4: Micrograph of Al-12%Si+3.3%M_o

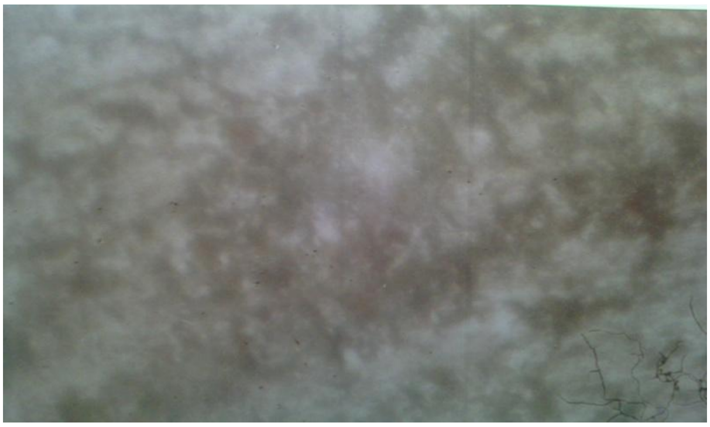

Plate 5: Micrograph of Al-12%Si+3.3%Cr

The results of the conducted experiments in tables 1 and 2 reveal clearly that both Cr and Mo affect the properties the same way. The hardness and tensile strength of the as-cast Al-12%Si alloy increase with the increase in weight percentage of Cr and Mo elements.

Addition of Cr and Mo from 0.55 to 5.00 wt% resulted to an increase in ultimate tensile strength, with corresponding decrease in ductility of both Cr and Mo cast alloys. It also show that the addition of Cr or Mo to Al-12%Si alloy impacted significantly on the hardness. The reason might be due to the precipitation of the inter-metallic compounds ($CrAl_2$ and M_OAl_{12}) which increased with increase in addition of M_O and Cr to the alloy system. The hardening of Al-Si alloy with Cr-addition is more effective than with the same amount of Mo the results show. The decrease in ductility of the alloy series is attributed to the hardening of the alloys due to the presence of intermetallic compounds or hardspots. Intermetallic compounds are known to be very brittle and of sharp melting temperature due to the strong chemical bonding. Overall, the hardness increases as the alloy content increases but shows a noticeable decrease at 3,3 %wt of the Cr and Mo alloy contents showing perhaps the presence of unrefined primary precipitates of brittle Si content or incoherent precipitates. This shows that the primary crystals of Si must be refined so as to accomplish higher hardness and tensile strength [10].

It is seen that the influence of Cr and M_o on ultimate tensile strength depends on their weight percentage and the tensile strength of Al-12%Si5%Cr is observed to be higher than that of Al-12%Si5%M_o. The reason for the increase in ultimate tensile strength as the percentage Cr is increased may be as a result of the strong metal bond interaction and formation of strong and finer grain complex precipitates of MoAl and $CrAl_2$ in the alloys which serve as a barrier to movement of dislocations. However, better mechanical properties upon addition of Cr can be explained thus, that Cr has a slower diffusion rate and forms finer dispersed phase than Mo [11]. These dispersed phases inhibit nucleation and grain growth of primary Al and Si. The phases also interfere with the solid-liquid interface and hinder the growth of the dendrites. This may well explain the mechanism by which flaky Si-platelets are converted to finer fibrous morphology. The morphology is found to be sensitive to the alloy contents [12] and optical microscopy analysis reveals homogenous solid solution as more of Cr and Mo were being added initially into the alloys. But the solubility deceases with a decrease in hardness at 3.3 %wt point of addition of both Mo and Cr contents

Conclusion

It is evidence from the results and analysis that the microstructure of eutectic Al-Si alloy is well modified by the addition of Cr and Mo elements in definite amounts.

It further demonstrate that the hardness of Al-12% alloy increases with the addition of the varying percentages of Cr and Mo, whereas the ductility of the modified Al-12%Si alloy system is found to decrease and the addition of Mo and Cr to Al--12%Si alloy have remarkably refined both the Si-platelets and the coarse columnar α-Al dendrites of the unmodified alloy to finer equiaxed α-Al dendrites, thereby increasing significantly the hardness and tensile strength for Al-12%Si5%Cr and Al-12%Si5%Mo alloys . The study outlines plan for cast Al-Si alloys property improvement which may aid manufacturing industries that produce automobile parts like brake pad, engine block and clutch system parts.

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