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MECHANICAL PROPERTIES OF CAST HYPOEUTECTIC AL-SI ALLOY IN HEXACHLOROETHANE-COATED MOULD

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Abstract

This work investigated the effect of hexachloroethane coated mould on the mechanical properties of hypoeutectic aluminium silicon alloy. An alumina based mould coating containing varying proportion (5% to 30%) of volatile hexachloroethane, C_2Cl_6 was prepared. The prepared mould coating was applied to form a coat of 2mm thick on the prepared metallic mould. The hypoeutectic aluminium-silicon alloy melted at 50°C superheat was poured into the already prepared coated mould and allowed to solidify. Then the effects of the volatile hexachloroethane, C_2Cl_6 concentration on the grain size, ultimate tensile strength (UTS), 0.2% Proof Stress, Hardness, percentage elongation and percentage reduction in area of the cast hypoeutectic aluminium-silicon alloy were assessed. The study revealed that the increase in C_2Cl_6 concentration in the mould coating up to 15 wt.% decreases the grain size of the alloy thereby causing increase in the mechanical properties (UTS), 0.2% proof stress, hardness, percentage elongation and percentage reduction in area) of the alloy. It was established that the optimum value of C_2Cl_6 concentration at which the mechanical properties were optimum is about 15 wt.%. Beyond this value, the C_2Cl_6 becomes deleterious to grain refinement due to rapid agitation in the mould.

Keywords: Hexachloroethane, Mould coating, Aluminium-Silicon Alloy,
Grain refinement, Mechanical properties.

1. Introduction

Generally speaking, the grain refinement of cast and wrought metals is not only beneficial in improving room temperature mechanical properties such as strength, hardness and ductility, but also results in reduction of hot tearing, hot cracking and time required for homogenization. It also contributes to a better feeding

Nomenclatures

C_2Cl_6	Hexachloroethane chemical formula
d	The average grain size, mm
d_α	Diameter of the α grain in the structure, mm
d_β	Diameter of the β grain in the structure, mm
L	Total length of the phase in question, mm
L_α	Length of the α grains in the structure, mm
L_β	Length of the β grains in the structure, mm
N	Number of grains occupying the intercept length
N_α	Number of the α grains in the structure
N_β	Number of the β grains in the structure
UTS	Ultimate tensile strength, kgf/mm^2
wt.%	Weight percent

Greek Symbols

α	The first phase present and representing the white patches on the microstructures
β	The second phase present and representing the grey patches on the microstructures

Abbreviations

AA TP 1 Test	Aluminium Association Standard Test Procedure No. 1 for Aluminium Grain Refiners
BHN	Brinell hardness number, HB
MLI	Mean linear intercept

characteristics and increased pressure soundness.

The mechanical properties of cast metals are determined to a large extent by their microstructures, and aluminium and its alloys are no exception to this basic principle [1]. The use of grain refinement in the aluminium industry is widespread, and its associated benefits for microstructure and properties are well documented. For some casting conditions, the solidification of smaller, more globular grains allows the mould to be filled more completely and avoid unfavourable micro- and macro porosity producing a sound casting [2].

In the last five decades, there has been rising interest in the grain refinement of aluminium and its alloys. A variety of the techniques for the same has been developed and used with varied success [3]. On a wider scope, the available techniques of grain refinement are grouped as thermal, chemical and mechanical methods. A variant of the mechanical methods known as Volatile Mould Coating (VMC) Process has been used recently for grain refinement of aluminium and its alloys with a huge success. Mould coating serve to prevent sticking of the casting to the mould, provide a smooth surface, and assist in controlling solidification so that sound castings are obtained.

Perhaps, as a result of such merits offered by this new technique that in recent past years, some interest has been shown in its application for the grain refinement of aluminium and its alloys. However, there is controversy in the available literature [3] regarding the optimum content of the volatile organic compound (such as hexachloroethane) to be used in the mould wash as well as the pouring conditions to be adopted.

Attempts have been made without much success in the past to optimize the use of this technique for the grain refinement of aluminium alloys. Therefore, this present research work is targeted at studying the optimal use of the technique by the establishment of the optimum conditions for grain refinement of hypoeutectic aluminium silicon alloys with respect to the hexachloroethane content in the mould wash.

2. Experimental Procedure

2.1. Mould wash and mould preparation

The mould coating materials used in this study comprised of 95% pure alumina powder and 95% pure C_2Cl_6 as the volatile organic substance. The base mould coating material was prepared by adding 240 g of water to 360 g of the 95% alumina powder of mesh size of 150 in a beaker. The aggregate prepared which served as a binder for the C_2Cl_6 was thoroughly mixed and divided into nine equal portions. To each portion, a measured quantity of 95% C_2Cl_6 crystals was added to form the mould wash with alumina slurry and C_2Cl_6 in proportions presented in Table 1.

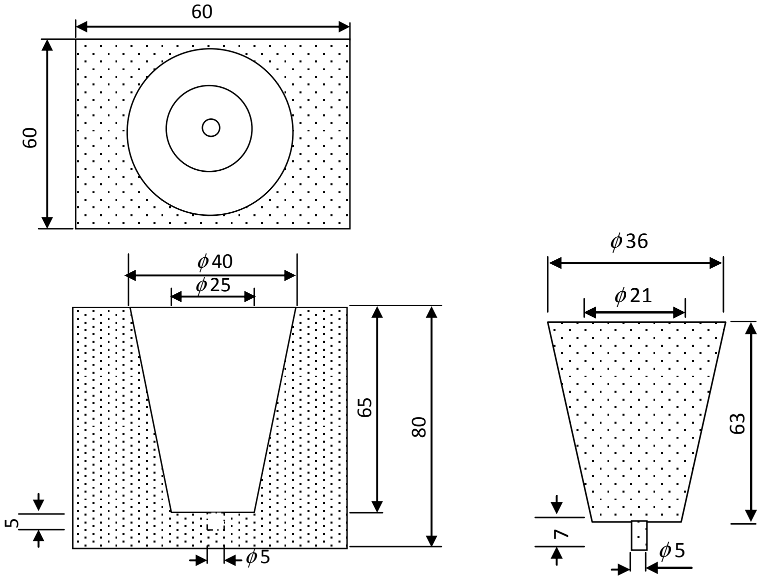
Table 1. Concentrations of the Prepared Mould Washes.

Mould wash	1	2	3	4	5	6	7	8	9
Alumina Slurry, (wt.%)	100	95	90	85	80	75	70	65	60
C_2Cl_6 content, (wt.%)	0	5	10	15	20	25	30	35	40

Three rectangular grey iron permanent moulds with dimension of 60 mm × 60 mm × 80 mm each were produced. Each of the moulds was designed to contain a mould cavity with opening diameter of 40 mm, base diameter of 25 mm and a depth of 65 mm, Fig. 1(a). Also, a central locating hole of diameter 5 mm and depth 5 mm was drilled at the base of the metal mould to receive a cone frustum described in Fig. 1(b). In accordance with the AA TP 1 Test, sufficient angle of taper, 6.58° was incorporated to enhance adequate feeding conditions, promote directional solidification so as to ensure production of macroscopic cavity-free and micro porosity-free hypoeutectic aluminium-silicon alloy ingots. In addition, the taper also allows for easy withdrawal of the cast ingots.

2.2. Ingots casting

A solid metal plug in the form of a frustum from a cone of 63 mm high with top and bottom diameters of 36 mm and 21 mm respectively was carefully machined with a locating pin of diameter 5mm and length 7mm, Fig. 1(b). The prepared alumina - hexachloroethane mould wash was carefully poured to almost fill the mould and then the plug is now positioned in the mould forcing the prepared slurry to fill the uniform 2 mm gap between the mould and the plug with the excess slurry collected at the top of the mould. The coated mould was allowed to dry for a period of 24 hours at ambient temperature and the plug carefully removed. The ease of removal was ensured with the help of parting powder with which the plug was initially rubbed. Thereafter, the aluminium alloy was melted in a graphite crucible pot using electrical furnace. The temperature of the melted aluminium alloy was raised by 50°C to a temperature of 768°C and degassed with chlorine tablet in an amount of about 0.25 wt.% of the molten metal [4]. The molten metal was thereafter poured into the already prepared coated mould, allowed to solidify, cooled in the mould and then shook out.



(a) Empty Mould **(b) Mould plug**

Fig. 1. Mould Units.

The coating and casting procedure were repeated for hexachloroethane concentrations of 10 wt.% to 30 wt.% respectively at 5 wt.% interval. Each group of the cast ingots was sectioned to obtain various test samples for hardness and tensile strength. Metallographic analyses were also made. The longitudinal view of the sectioned ingot is shown in Fig. 2.

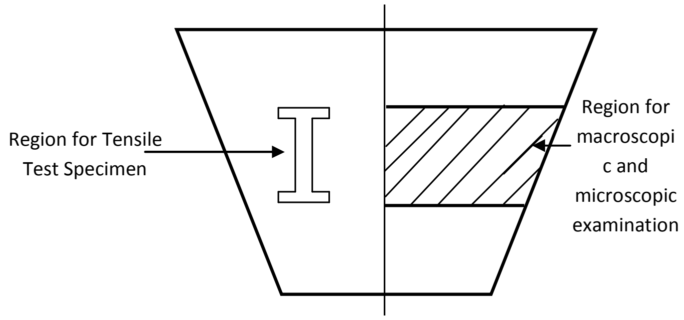


Fig. 2. Longitudinal Section of Cast Ingot.

2.3. Tensile test

Standard tensile test specimens were also prepared in accordance to *BS18* "Methods for Tensile Testing of Metals" [5] and their tensile strengths determined using Monsanto Tensometer. The UTS was measured and 0.2% proof stress, % elongation and % reduction in area were determined for each of the cast samples.

2.4. Hardness test

Brinell hardness number *(BHN)* was also determined using Brinell Hardness Tester. The already prepared flat surface of each of the cast ingot was indented using 5 mm hardened steel ball under a consistent load of 250 kgf applied for about 15 seconds. The hardness value was obtained by matching diameters of indentation with corresponding hardness value on a Standard Table of Brinell Hardness Number.

2.5. Microstructural analysis

The preparation of samples for microexamination involved sampling, flattening, grinding, polishing and etching. Each sample was cut with the help of automatic sample cutter to a suitable size (ϕ10 mm × 10 mm). The samples were too small to be handled with ease and so they were mounted on bakelite. The mounted samples were ground on grinding wheels. Polishing was then carried out on various grades (220, 320, 400 and 600) of emery papers (silicon carbide) of increasing fineness. This was followed by the final polishing which was carried out on a rotating disc covered with Selvyt cloths (3 and 1 microns respectively) soaked in water and sprinkled with alumina slurry. Using a rotating Universal Polishing machine at a speed of 100-400 rpm and the polishing was carried out until the surface of the sample became scratch-free and mirror like.

Etching was carried out by a swabbing technique. The etchant used was 10% $NaOH$, which preferentially attacked the grain boundaries and exposed the grains. The specimen was quickly removed after the surface became dull and washed in running water. The surface of the specimen was then dried by spraying with methylated spirit and blown with warm air. The microstructures of the samples were then observed and taken using Olympus digital camera model *C5050Z.*

2.6. Determination of grain size

The mean linear intercept method was used in this study for the determination of the grain size of the phase(s) present in the hypoeutectic aluminium silicon alloy developed. The method involves measuring the chord length defined by the intersection of a random straight line with the grain boundaries in the plane section.

The Mean Linear Intercept (MLI) method sometimes called the Heyn intercept is used as a measure of grain size in both single-phase and multiple-phase alloys. The formula for the determination of the grain diameter is given by

$$d = L/N \tag{1}$$

In this procedure, an 80 mm × 80 mm square box was drawn on a tracing paper. This was divided into 10 mm × 10 mm square boxes so that there were 9 vertical and 9 horizontal lines (i.e., 18 lines in all). The tracing paper was superimposed on the micrograph to be studied so that the 80 mm × 80 mm square box covered the micrograph alone completely.

Each of the 18 lines in the box was numbered from the horizontal line serially from L_1 to L_9 while vertical lines were similarly numbered but from L_{10} to L_{18}. Starting from line 1, L_1, the number of the α phase, β phase, etc. that cut through the line were respectively recorded against it. The length of individual grains were summed and recorded against it as L_α, L_β, etc. The procedure was repeated for L_2 up to L_{18} respectively. The number of grains for each of the phases for the 18 lines and L_α, L_β, etc. were summed up.

When studying a line, it would be assumed that all the other 17 lines were not present, so that only the grain that cut through it were considered (counted) and the individual length summed up to be recorded under L_α, L_β, etc. Let the shaded grains be α phase and the unshaded be β. By modifying Eq. (1) to Eq. (2), the grain sizes were thereafter determined

$$d_\alpha = \frac{\sum L_\alpha}{\sum N_\alpha} \quad \text{or} \quad d_\beta = \frac{\sum L_\beta}{\sum N_\beta} \tag{2}$$

3. Results and Discussion

3.1. Results

The chemical analysis of the alloy used is presented in Table 2. The major constituents are aluminium, silicon and copper the content of which are 90.0%, 6.0% and 2.0% respectively.

Table 2. Chemical Composition of the Prepared Hypoeutectic Aluminium Silicon Alloy.

Elements	Al	Si	Cu	Fe	Mg	Zn	Pb	Others
Percent Composition (wt.%)	90.0	6.0	2.0	0.6	0.2	0.5	0.1	0.6

The results of mechanical properties are presented in Table 3 while the micrographs of the cast alloy at various C_2Cl_6 concentrations are presented in Figs. 3 to 9. The curves of the mechanical properties are shown in Figs. 10 to 12. The result of the grain size analysis is presented in Table 4 and Fig.13.

Table 3. Effects of C2Cl6 on the Mechanical Properties of Hypoeutectic Al-Si Alloy.

% C_2Cl_6 in mould coating	UTS (MPa)	0.2% Proof Stress, (MPa)	Hardness (BHN)	% Elongation	% Reduction in Area
0	27.6	12	79.6	3.0	3.6
5	32.2	18	92.5	3.5	4.1
10	35.0	22	100.8	4.3	4.7
15	38.0	25	110.5	4.6	5.2
20	37.5	23	108.8	4.5	4.9
25	37.1	23	107.2	4.4	4.7
30	36.7	23	105.5	4.4	4.6

3.2. Discussion

Figures 3 to 9 show the microstructures of the hypoeutectic aluminium-silicon ingots cast at different C_2Cl_6 concentration. The different phases present in the microstructures are aluminium grains, silicon patches at the grain boundaries and in some instances impurities as shown on Figs. 3 to 9.

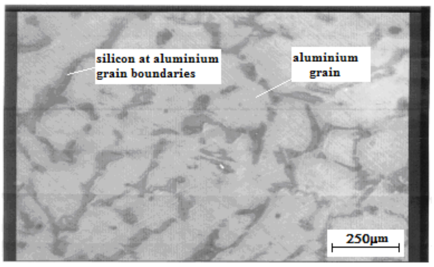


Fig. 3. Micrograph of the Ingot Cast without any Mould Coating.

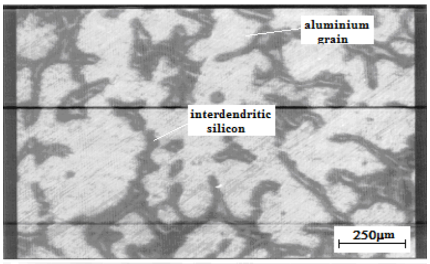


Fig. 4. Micrograph of the Ingot Cast with 5% Hexachloroethane.

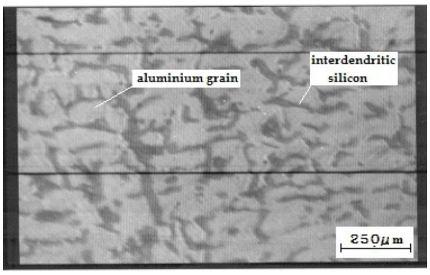


Fig. 5. Micrograph of the Ingot Cast with 10% Hexachloroethane.

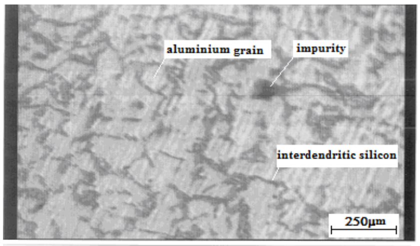


Fig. 6. Micrograph of the Ingot Cast with 15% Hexachloroethane.

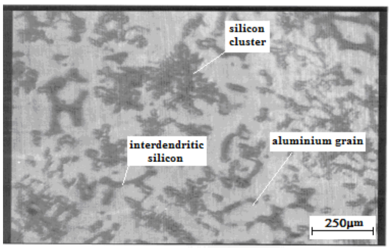


Fig. 7. Micrograph of the Ingot Cast with 20% Hexachloroethane.

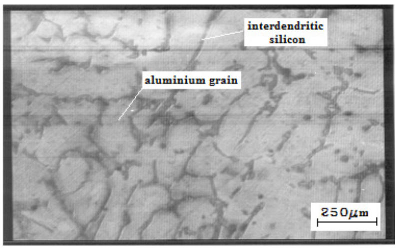


Fig. 8. Micrograph of the Ingot Cast with 25% Hexachloroethane.

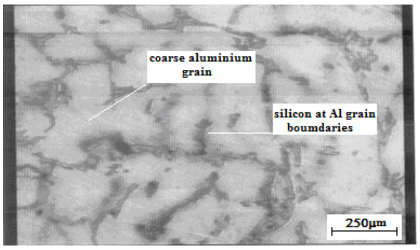


Fig. 9. Micrograph of the Ingot Cast with 30% Hexachloroethane.

Generally, all the structure of the castings essentially comprise of the mixtures of aluminium grains, silicon crystals (dark grey) and aluminium-silicon eutectic as well as various intermetallic phases formed from other alloying additions (Mg_2Si, $CuAl_2$), which ranges from light grey script to black [6, 7].

It was shown that the ingot cast without any mould coating has the lowest hardness value (Fig. 10). However, as hexachloroethane was introduced into the mould coating and its concentrations progressively increased from 0 – 15 wt. %, the hardness value increased from 79.6 BHN up to 110.5 BHN. Above 15 wt. % hexachloroethane concentration the hardness value decreased. This shows that the optimum value of Hexachloroethane in alumina based mould wash which gives us the maximum hardness value (110.5 BHN) is 15 wt.%.

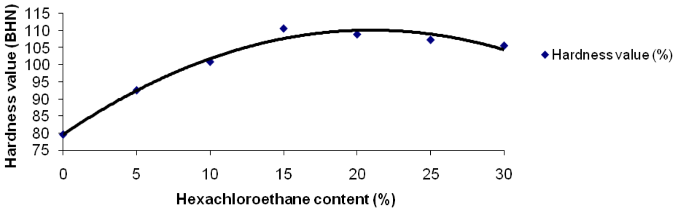


Fig. 10. Effect of Hexachloroethane Content on Hardness Value.

The ingot cast without mould coating also has the lowest ultimate tensile strength 27.6 MPa (Fig. 11). With the introduction of mould coating the tensile strength value picked up, and the introduction and progressive increase of Hexachloroethane concentration into the mould wash also gave a progressive increase in the ultimate tensile strength values up to 15 wt.% of Hexachloroethane (Fig. 11).

Further addition of Hexachloroethane above the 15 wt.% decreases the ultimate tensile strength. Therefore, it can be inferred that the optimum value of hexachloroethane in the mould coating that gives the maximum UTS of 38.5 kgf/mm^2 (385 N/mm^2) is 15 wt.%.

The ingot cast without any mould coating produced the lowest 0.2% proof stress values (Fig. 11). As mould coating is introduced, the values of the proof stress rose up to about 25 kgf/mm^2 with 15 wt.% hexachloroethane in the mould wash. However, this value dropped as more concentrations of hexachloroethane is introduced. This implies that the optimum value of hexachloroethane content in the mould wash that gives the highest 0.2% proof stress is 15 wt.%.

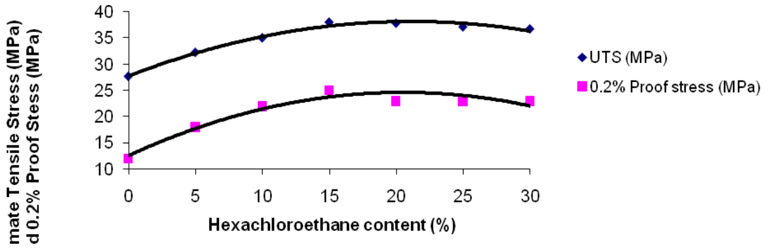


Fig. 11. Effect of Hexachloroethane Content on Ultimate Tensile stress (UTS) and 0.2% Proof Stress.

It was revealed that the ingot cast without any mould coating gave the lowest values of both the % elongation and % reduction in area which stand at 2.9% and 3.4% respectively (Fig. 12). When alumina coating was introduced the values rose to 3.0 and 3.6 for % elongation and % reduction in area respectively. However, with the introduction and increase of hexachloroethane concentrations in the mould wash, corresponding increase for both properties (i.e. % elongation and % reduction in area) occurred up to 15 wt.% hexachloroethnae above which a slight drop in the slopes of the curves (Fig. 11) occurred. This implies that the optimum concentration of hexachloroethane in the mould wash that give the maximum % elongation and % reduction in area of 4.6 and 5.2 % respectively is 15 wt. %.

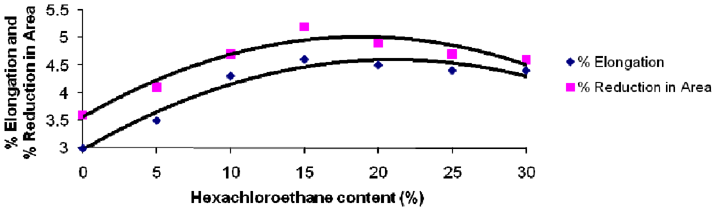


Fig. 12. Effect of Hexachloroethane Content on % Elongation and % Reduction in Area.

The results obtained from grain size determination presented in Fig. 13 (or Table 4) revealed that the grain size of the cast ingot was 31.8 μm when no surface coating was given to the mould. However, when the mould surface was coated with alumina the value rose to 21.4 μm but on the introduction of hexachloroethane, the grain size value reduces. The grain size attained the lowest value of 8.0 μm when the C_2Cl_6 content was increased to 15 wt.%. Beyond this value, the grain size started increasing again.

Table 4. Effect of Hexachloroethane Concentration in Mould Coating on Grain Size.

C_2Cl_6 content in the coating, wt.%	Uncoated	0	5	10	15	20	25	30	35	40
ΣL_α mm	1117	1128	947	1195	669	768	962	1011	1282	1404
ΣN_α mm	90	132	123	185	209	156	186	161	133	134
Magnification, M	400	400	400	400	400	400	400	400	400	400
D_α (μm)	31.0	21.4	19.2	16.1	8.0	12.3	12.9	15.7	24.1	26.1

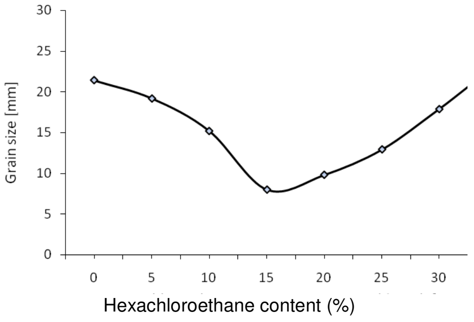


Fig. 13. Effect of Hexachloroethane Content on Grain Size.

The large grain size observed when there was no or lower amount of hexachloroethane in the mould wash could probably resulted from the fact that there was no enough gas production and the pressure was low to cause the required agitation. Therefore, any metal cast at these conditions (below the optimum condition) depends solely on the mould/metal interface solidification reactions [8, 9]. However, further increase in the hexachloroethane concentration beyond the optimum amount (i.e. 15 wt.%) causes increased amount of gas production promoting more and more of violent convection and turbulent flow which in turn may cause some of the nuclei produced being remelted in the superheated liquid. This increased convection according to Cibula A. (1949-50) [10], Tiwari et al (2001) [3] and Beeley (2001) [5], causes local thermal fluctuations in the liquid and thus only a fewer nuclei are left to survive and grow producing a relatively coarse grained structure and consequent decrease in the mentioned mechanical properties of hardness, ductility, ultimate tensile strength and 0.2% proof stress.

Thus, suffice to conclude that the 15 wt.% hexachloroethane concentration in the mould wash is the optimum one for effective grain refinement of the hypoeutectic aluminium silicon alloy and any further increase in the content of the compound causes coarsening.

Therefore, generally speaking, it is obvious as shown in Figs. 10 to 12 that all the tested mechanical properties; hardness, strengths and ductility (elongation and reduction in area) increase with increase in the concentration of hexachloroethane up to 15 wt.%. Beyond this they decrease with increase in the concentration of hexachloroethane in the mould coating. Obviously, the increase in mechanical properties is due to the refinement of the grains brought about by the introduction of the hexachloroethane.

4. Conclusions

The maximum mechanical properties (the hardness, ultimate tensile strength, 0.2% proof stress and ductility) of the prepared Aluminium-Silicon ingot were obtained when the C_2Cl_6 concentration in the hexachloroethane based mould wash was at the optimum value of 15 wt.%. This was attributed to appropriate agitation in the melt caused by the evolved gases during casting that brought about desired grain refinement.

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