EFFECT OF SHORT CYCLE HEAT TREATMENT AND COOLING RATE ON MICROSTRUCTURE AND MECHANICAL PROPERTIES OF RECYLED ALUMINIUM SAND CASTING

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Effect of short cycle heat treatment and cooling rate on microstructure and chemical properties of recycled aluminium sand casting

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DECLARATION

This thesis is my original work and has not been presented for a degree in any other university.

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DEDICATION

This work is dedicated to those at the centre of my being: God, Mum, Dad, Emily, Glo, Malu and Mari.

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ABBREVIATIONS

ASTM	American Society for Testing and Materials
BS	British Standards
DAS	Dendrite Arm Spacing
JIS	Japanese Industrial Standards
JKUAT	Jomo Kenyatta University of Agriculture and Technology
MPa	Mega-pascal
PS	Proof Stress
SDAS	Secondary Dendrite Arm Spacing
ST	Solution Treatment
UTS	Ultimate Tensile Stress
YS	Yield Stress

NOMENCLATURE

A	Surface Area[m^2]
α	Lift Angle[°]
α-Al	Primary Aluminium Matrix
B	Mold Constant
β	Swing Angle[°]
D	Distance from the center of the revolving axis to gravity center[m]
d	Mean Grain Diameter[μm]
d_1	Major Diameter of Pyramid Indentation [μm]
d_2	Major Diameter of Pyramid Indentation [μm]
E	Impact Energy[J]
f_o	Materials constant for the starting dislocation stress[MPa]
f_y	Yield Strength[MPa]
N	Number of Grains per Square Inch at a Magnification of 100
n	Grain Size Number
G_E	Grain Size Index
k	Strengthening Coefficient
P	Total Weight[kg]
R	Mean Cooling Rate[°C/s]
V	Volume[m^3]

ABSTRACT

Heat treatment is an essential part of manufacture of aluminium castings. This is because it improves the mechanical properties of the casting such as hardness, ductility and tensile strength. T6 is one of the most popular heat treatment procedures used in heat treating aluminium alloys and consists of three stages; the first is solutionising of the cast part in a furnace at 540°C for 6 hours, then quenching in water at 60°C before aging in an oven for 3 hours at 170°C.

This study investigated the effect of heat treatment and cooling rate on the microstructure and mechanical properties of aluminium alloy A356 with a view to determine if a short solution heat treatment could be achieved without adversely affecting the final mechanical properties of the material.

The aluminum alloy A356 was obtained from used motor vehicle wheels that were melted and cast into ingots. During melting a sample was collected and analysed to determine the metal's precise chemical composition. The ingots were then melted and poured into sand molds assembled with a metal chill in one of the walls. On the opposite end, the mold was designed to have the sprue, so that across the casting there would be regions of distinct cooling rates. Thermocouples mounted in the mold captured the varying temperatures across the casting which allowed the casting to be cut along sections having distinct cooling rates. These sections were further divided into five sets of specimens that were solution heat treated for periods of 30 minutes, 1 hour, 3 hours and 6 hours while one was retained in as-cast state. Microstructural analysis and mechanical tests including tensile, ductility, hardness and impact tests were then carried out on these specimens.

Results showed that a casting of 2.11°C responded best to short heat treatment as it achieved 92% of the maximum yield strength when solution treated for 30 minutes. Over the same period it achieved maximum Vickers hardness and ductility values of 60 and 5% respectively. This was attributed to the fully spheroidised and fragmented structure that was observed after only 30 minutes of solution treatment. A study of the local foundries established that there was no application of standard melt treatment procedures; foundry men lacked relevant industry training and the level of education of the majority was low. This concluded that for a short heat treatment process to benefit local foundries a holistic training approach needed to be conducted.

CHAPTER ONE

1.0 INTRODUCTION

1.1 Preamble

The unique combinations of properties provided by aluminium and its alloys make it one of most versatile and attractive metallic materials. This metal has a broad range of applications from soft highly ductile wrapping foils to the most demanding heavy engineering applications. The metal also has a low density and high specific strength that allowed production and construction of lighter automobiles, marine vehicles and aircraft resulting in fuel savings and increased payload [1, 2].

In pure form, aluminium is ductile, non-magnetic with high electrical and thermal conductivity. This suits its applications in electronic items and production of high voltage power transmission systems. Pure aluminium also has non-sparking characteristics that allows it to be used in tools that are employed near flammable and explosive materials [3, 5–7].

In production engineering, properties of interest in aluminium and its alloys are of a mechanical nature. Tensile strength, amount of strain at yield, hardness, ductility and fatigue behavior are some prime considerations made in its selection. Others are its wear characteristics and impact strength.

These properties are primarily influenced by the material's physical nature as well as chemical constitution; physical aspects include microstructure, grain size, grain structure and orientation. Chemical aspects relate to the elemental chemical constitution, the concentration and overall alloying effect. In order to achieve a material of superior mechanical properties, aluminium is alloyed with other elements such as zinc to improve corrosion resistance for use in marine vehicles, or with magnesium to improve abrasion and wear characteristics for use in diesel engines pistons. Other elements are used depending on desired properties of the final alloy. Common aluminium alloy classifications are Al-Si-Mg based alloys, Al-Si-Cu alloys and Al-Si-Cu-Mg based alloys. Of these classifications, the most preferred in applications requiring strength, good castability and use as secondary alloys are Al-Si-Mg based alloys [8].

Other processes used to improve mechanical properties of aluminium are work hardening and heat treatment. Heat treatment in particular is most preferred as it can be used to control different properties in a material. By simply varying the treatment process a high ductility may be achieved, the materials abrasion resistance increased or a materials yield strength substantially improved. This is done by exposing a part to temperatures just below its melting point for several hours in a furnace or oven. The result is usually a light weight part of high strength and generally better mechanical properties. This process is useful especially in manufacture of automobile parts such as gear box housings, exhaust manifolds, oil sumps, cylinder heads and aluminium alloy wheels [9, 10].

In Kenya, small and medium size foundries are known to use aluminium to cast items such as motor vehicle suspension spacers, cooking pots and pans and items for decorative purposes that do not require heat treatment. Large foundries on the other hand cast in mass items of greater commercial value such as water pumps, gear box housings for winch pulleys, gears and motor cycle parts.

1.2 Problem statement

A short cycle heat treatment and controlled cooling process can enable the production of high strength aluminium castings with high resistance to fracture, corrosion, cracking as well as high thermal and dimensional stability. The process can therefore form an important and integral part of the manufacture of castings especially those cast in sand molds. Heat treatment is known to increase the mechanical properties of castings by up to double the initial values. However such substantial gains are only achieved in castings of rapid cooling such as those cast in permanent molds. Parts cast in molds of slow cooling such as sand molds and investment castings do not achieve such large gains due to the slow cooling and solidification process predisposed in them. Close control of the cooling process, modification of the castings microstructure and varying of the solution heat treatment time can be used to determine optimum casting conditions that can be employed to achieve maximum gain of mechanical properties especially in the manufacture of sand castings.

1.3 Objectives of the study

1.3.1 Main objective

The primary objective of the study was to determine the effect of short heat treatment process and cooling on microstructure and mechanical properties of an Al-Si alloys as well as ability of the local industry to adopt the technology.

1.3.2 Specific objectives

In order to achieve the main objective, the following were the specific objectives:

1. To cast aluminum alloy A356 in sand moulds and modify the microstructure.
2. To determine sections of distinct cooling rates in the alloy castings and determine their effects on mechanical properties.
3. To carry out heat treatment on the castings and determine the effect of varying the treatment periods on microstructure and mechanical properties of the alloy.
4. To conduct a survey of local foundries to determine level of skills, competencies, education and challenges of practitioners with a view to determine if they would benefit from knowledge of better heat treatment techniques.

1.4 Scope of the research

The research was limited to aluminium-silicon alloy A356 obtained from scrap metal. Tests conducted were microstructure analysis, impact strength tests, hardness tests, ductility and tensile tests.

1.5 Justification of the study

A well established cooling rate and shortened heat treatment process will empower the foundry industry especially in the production of mechanically sound items while employing a shorter lasting heat treatment procedure. The study on the industrial foundry survey will also highlight the ability of the local industry to adopt to practices that will enable them compete favorably with other international producers.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Introduction

The most commonly used methods of casting aluminium alloys are sand casting and permanent mould casting. Sand castings are cheaper to use and develop intricate shapes and forms. Permanent moulds on the other hand are costlier to develop but are suitable for production of large numbers of dimensionally similar components [5, 6, 11, 12].

In production of high strength aluminium parts such as gear box housings, pulleys or gears, heat treatment is often applied to alter their chemical and physical properties. This improves strengths and maximizes other mechanical properties such as the materials hardness and ductility [7]. T6 procedure is a widely applied heat treatment method that involves solutionising parts at an elevated temperature, quenching and artificial ageing. This process is highly favored as it imparts two major beneficial effects; first is an improved ductility and resistance to fracture and second it elevates an alloys yield strength and resistance to impact [13, 14].

The first benefit is achieved through spheroidisation of eutectic silicon in microstructures and is realized during solution treatment time while the second is achieved throughout the entire process of solutionising, quenching and ageing [13, 15, 16].

In order to achieve a good heat treatment, a casting must be of sound quality. This is dictated by factors that are extrinsic and intrinsic to a casting. Extrinsic factors affect a casting at the melting stage and include processes that purify metal while in molten state. These include degassing, melt filtration and alloying to achieve required concentrations of its standard constitutive elements. Intrinsic factors affect the crystal structure and directly influence the final materials properties. Some of these are a metals solidification rate, dendrite arm spacing, grain structure and microstructure [14,17].

2.2 Solidification and Dendrite Arm Spacing of A356 Aluminium Alloys

The most critical period in a casting process is solidification. It is at this time that most defects such as gas porosities, blow holes, solidification shrinkage and hot tears occur. Understanding dynamics of solidification is therefore critical to manufacture of sound sand castings.

While a pure metal or eutectic alloy solidifies, temperature remains constant. This is called thermal arrest and is caused by evolution of latent heat that keeps liquid metal at freezing temperature until all liquid has solidified and no more heat can be evolved [1]. Figure 2.1 is a temperature time curve of a pure metal and also illustrates thermal arrest, superheat, local and total solidification time. In pure aluminium thermal arrest occurs at a temperature of 660.4°C [14].

The cooling behavior is important as it can be used to control quality of a casting as well as be manipulated to achieve desired mechanical properties. Superheat affects a metal's cooling rate which also directly affects grain size and microstructure. If the magnitude of superheat is large it will also imply that there will be more time for liquid material to flow into spaces of a mould with intricate design. A major advantage of large superheats is the possibility of casting thin walled large surface elements manufactured with high accuracy and dimensional stability [18].

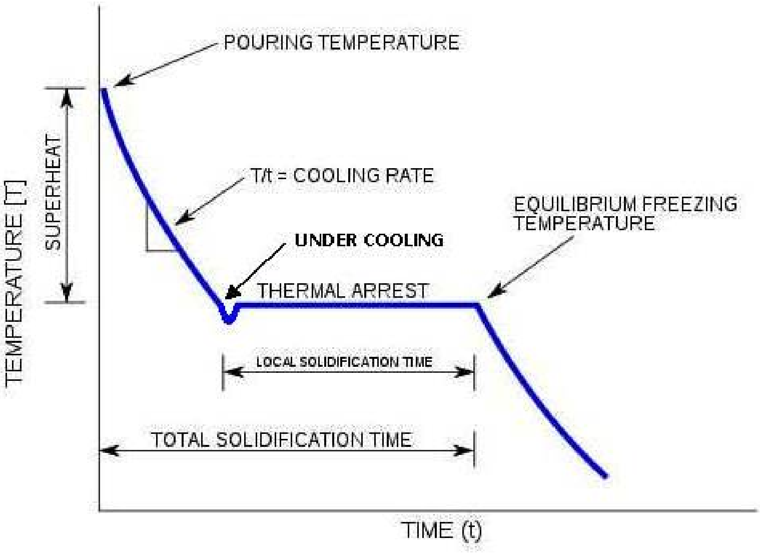


Figure 2.1: Cooling curve of a pure metal or eutectic alloy [1].

Solidification of alloys on the other hand occurs over a range of temperatures. The metal transitions from liquid phase through to a semi solid and finally to a solid. This range is referred to as "mushy zone" and temperature at which the first crystal solidifies corresponds directly to liquidus temperature on a phase diagram. The end of solidification is at a lower temperature that corresponds to solidus temperature. Figure 2.2 shows a phase diagram and cooling curve of an isomorphous alloy.

In Al−Si alloys the liquidus and solidus temperatures depend on the constitutive chemical composition of the alloy but principally the amount of silicon [1]. Table 2.1 shows concentrations of silicon for selected Al-Si alloys and corresponding liquidus and solidus temperatures.

Table 2.1: Silicon concentrations and freezing range of Al-Si alloys [12].

Alloy	**Silicon Content**	**Classification**	**Freezing Range(°C)**
Low silicon	4-6%	LM 4	625-525
Medium silicon	7.5-9.5%	LM 25	615-550
Eutectic silicon	10-13%	LM 6	575-565
Special hypereutectic alloys	above 16%	LM 30	650-505

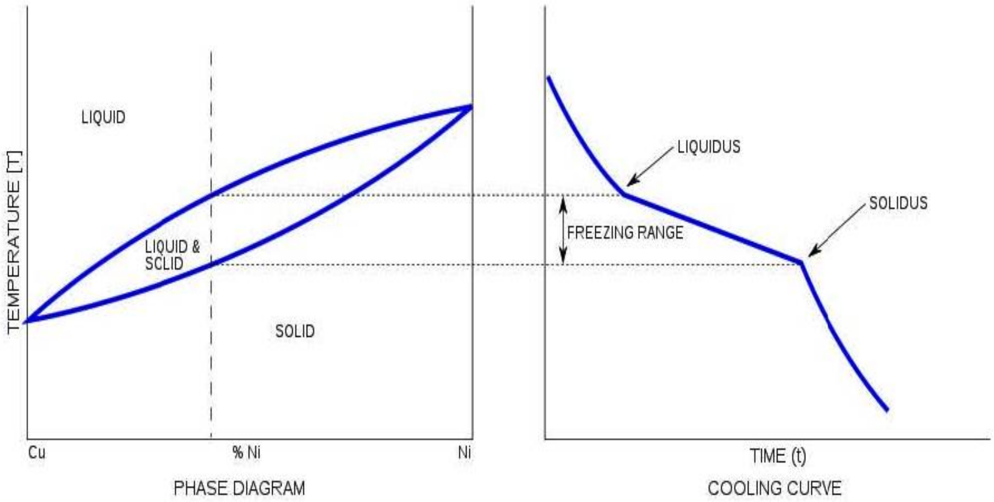


Figure 2.2: Cooling curve of an isomorphous alloy [1].

Solidification in metals occurs through nucleation and growth of crystals. Nucleation takes place when a crystal develops from a simple unit of appropriate structure in liquid metal referred to as a nucleus. Growth of a crystal then occurs by addition of atoms of liquid metal according to its lattice pattern and assumes a tree like shape called a dendrite. The dendrite, like a tree, has the main trunk with branches arising from it; the trunk is referred to as the primary arm while branches are referred to as secondary arms [1]. Figure 2.3 shows dendrites in an aluminium casting.

Dendrites grow in this way because heat is dissipated faster from a point; temperature therefore falls most quickly at the tips leading to formation of an elongated skeleton structure. Dendrite arms continue growing on the skeleton structure thickening at the same time until all spaces between them are filled and solidified. Meanwhile the outermost arms get into contact with neighboring dendrites that have been growing independently. The process ends when further growth is impeded by neighboring dendrites and any remaining liquid atoms attached to present arms [12, 19].

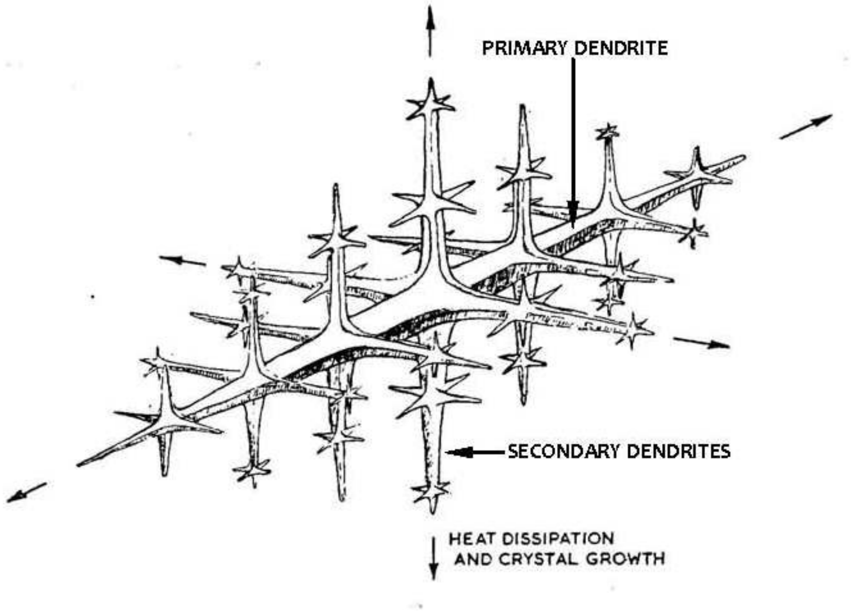


Figure 2.3: Primary and secondary arms of an aluminium A356 crystal [2]

When pure metals are observed under a microscope no dendrites are observed as all atoms are identical. However in alloys and pure metals with large amounts of impurities evidence of dendrites will be visible under a microscope. This is because impurities tend to remain in the molten portion as long as possible and are the last to solidify in the spaces between dendrites. When viewed under a microscope these impurities are clearly discernible and outline the dendrite boundaries [5,19,20].

The distance between arms is called Dendrite Arm Spacing (DAS) and that between secondary arms the Secondary Dendrite Arm Spacing (SDAS). To measure SDAS a micrograph of the metal is taken and groups of aligned secondary cells selected. A line is then drawn from the edge of one of the cells to another along these cells. The length of the line is then determined and divided by number of dendrite cells falling between the marked edges. This is repeated over several fields and averaged to determine SDAS. If tertiary arms are formed at smaller spacing, then SDAS would be measured between these arms [5, 21]. Figure 2.4 shows the growth of dendrites cells, their orientation within grains and how SDAS is measured [22].

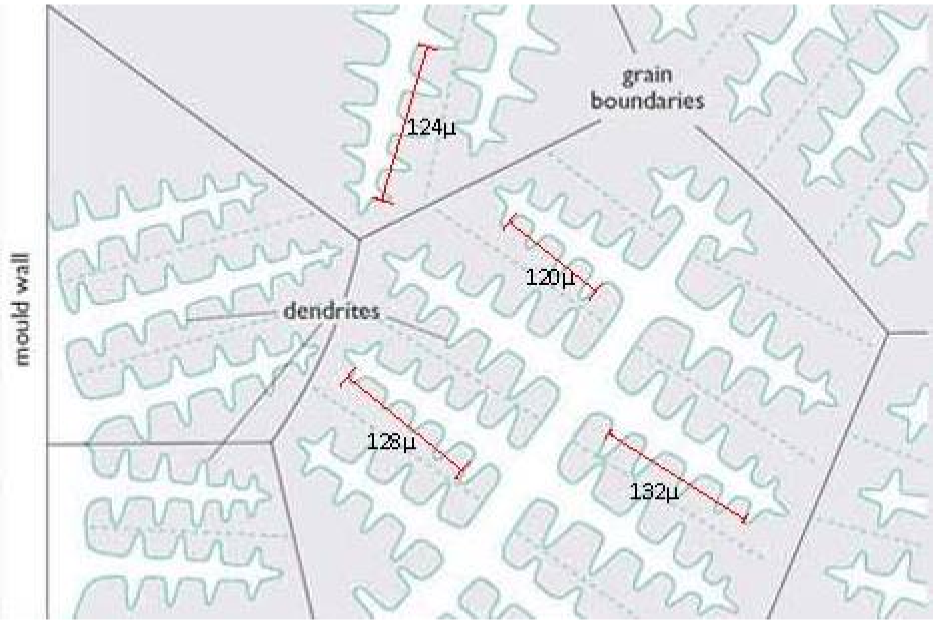


Figure 2.4: Growth of dendrites in grain cells and measurement of SDAS [2].

The size of SDAS is a function of cooling as the metal transitions through the mushy zone. Slow cooling through the mushy zone leads to a small degree of under cooling at the beginning of solidification resulting in formation of few nuclei and larger crystals and dendrite arm spaces. When the cooling rate is fast there is a higher degree of undercooling resulting in large number of nuclei hence many smaller crystals and dendrite arm spaces.

The empirical equations 2.1, 2.2 and 2.3 relate SDAS to solidification time, temperature to solidification time and solidification time to size of casting (Chvorinov's Rule) respectively:

$$SDAS = KR^m \tag{2.1}$$

Where m and K are constants dependent on alloy composition and are 39.4 and -0.317

respectively for aluminium alloy A356 [21].

$$R = \frac{dT}{dt} \tag{2.2}$$

Where R is mean cooling rate of primary aluminium dendrite cells during solidification, T is temperature and t is time in seconds:

$$t = B\left(\frac{V}{A}\right)^{n} \tag{2.3}$$

Where t is solidification time, n is a constant, B is mold constant, V is volume and A Surface Area.

2.3 Grain Size and its effect on Yield Strength

Dendrites originating from the same nucleus retain the same orientation and are bound within a common boundary to form a grain. DAS, grain size and grain structure of an Al-Si alloy are determined by cooling of the metal through the mushy zone. The DAS varies between 10 μm for a super cooled alloy to 200 μm in slow cooling castings of large volume. Grains of foundry alloys range between 0.1-10 mm and their structures may be equiaxed or columnar. Eutectic silicon appears as plates of up to 2 mm in length in unmodified alloys or spheres of less than 1 μm in heat treated alloys [23, 24].

During solidification the process of nucleation and growth varies across the metal resulting in varied grain orientations. At the metal mould interface, nucleation is faster than the rate at which cells grow resulting in many fine equiaxed grains forming a solid layer of metal.

Table 2.2: Hall-Petch constants for selected metals. [24]

Metal	f_o **(MPa)**	**k (MPa.mm$^{o.5}$)**
Aluminium	15.7	2.16
Titanium	78.5	12.75
Arco Iron	74.5	18.44
Copper	25.5	3.53

As more heat is dissipated into the mould the temperature gradient is lowered and heat extraction from the melt reduces. At this point columnar grains begin forming and grow on the first layer of solidified metal. Growth of this structure continues until the core of the casting where equiaxed grains are again formed. This zone forms coarse and randomly oriented grains that prevent growth of columnar grains and the material in this zone displays isotropic behavior [1, 8].

The size and shape of grains are important as they determine the material's mechanical properties. Smaller grains result in increased grain boundary therefore dislocations in grains move only short distances before encountering a boundary. Increased boundaries therefore limit propagation of dislocations resulting in materials of greater strength. The relationship between a material's grain size and yield strength is given by the Hall-Petch equation (see eq. 2.4). Table 2.2 gives Hall-Petch constants for some common metals [24].

$$f_y = f_o + \frac{k}{\sqrt{d}} \tag{2.4}$$

Where f_y is yield strength, f_o is a materials constant for starting stress for dislocation movement (or the resistance of the lattice to dislocation motion), k is strengthening coefficient and d is mean diameter of grains. In aluminium f_o is found to be 15.7 MPa and k is 2.16 MPa/mm^2 [24].

The size of the grain is designated by either grain size number or grain size index.

Equation 2.5 is an ASTM formula where N is number of grains per square inch at a magnification of 100 and n is the Grain Size Number. Equation 2.6 is the grain size index defined by BS as the number of grains per square millimeter at a magnification of 1. G_E is the Grain Size Index [4, 22].

$$N = 2^{n-1} \tag{2.5}$$

$$N = 2^{G_E+3} \tag{2.6}$$

2.4 Heat Treatment of Aluminium Alloys

Heat treatment provides an efficient way of manipulating mechanical properties of metal alloys by controlling the rate of diffusion and cooling within the microstructure. The heating process changes the microstructure and affects residual stresses in a material thus enabling many of today's technological achievements [9].

When an alloy is first cast, two types of materials are formed: intermetallic compounds (chemical compounds) and solid solutions. Intermetallic compounds lie in relatively large particles along grain boundaries resulting in points of weakness [10, 16]. To overcome this condition, a material is heat treated at elevated temperatures for a predetermined period of time to disintegrate intermetallic compounds. This increases solubility and dispersion of metal elements held in intermetallic compounds into grain cells resulting in higher tensile strengths, ductility, resistant to fracture [25].

Figure 2.5(a) shows coarse particles of $CuAl_2$ compounds in grain boundaries before heat treatment. In this state, aluminium can only absorb small amounts of copper in solution at room temperature. Figure 2.5(b) shows the metal after heat treatment with copper disintegrated and dispersed resulting in increased concentrations within the grain cell. A casting may undergo one or a combination of heat treatment processes depending on desired outcomes. Most common processes are solution treatment, quenching, annealing and ageing; each combination has a unique effect and results in materials having different qualities [26]. Table 2.3 shows tempers designated by prefixes representing different heat treatment combinations. The success of any heat treatment process is measured by repeatability of the heat treatment cycle from one production run to the next, heat distribution (uniformity) across a part, rate of heat transfer to the part and how close the part can be brought to its solidus temperature without overheating (overheating leads to incipient melting and granular corrosion that negatively affect a materials ductility). In principle the duration of a heat treatment process must be long enough and temperature high enough to allow maximum dissolution and homogenization of alloying elements. This means that for a successful process the equipment must provide reliable and precise temperatures in heating chambers.

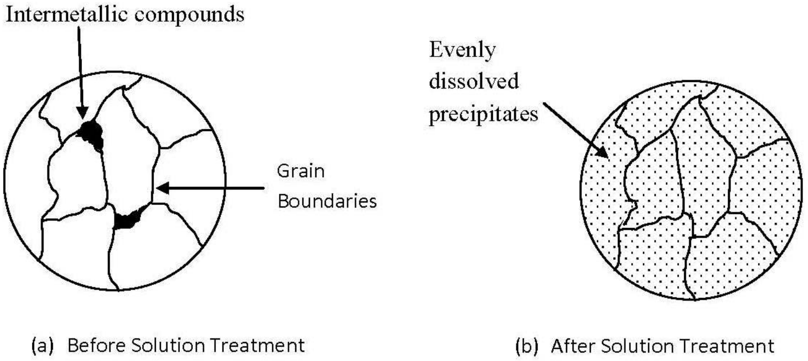


Figure 2.5: (a) Large inter-metallic particles along grain boundaries before solution treatment and (b) evenly dissolved particles after solution treatment. [20]

In most industries, heat treatment is carried out in hot air furnaces because of their relatively cheaper costs. Air chambers are however inefficient at transferring energy to parts leading to long heating periods and increased energy consumption. Also when large batches are heat treated, precision control is difficult to maintain resulting in

Table 2.3: Heat treatment suffixes [27]

Condition	**Suffix**		
	UK	USA	EN
As cast	M	F	F
Annealed	TS	O	O
Controlled cooling from casting and naturally aged	-	-	T1
Solution heat treated and naturally aged where applicable	TB	T4	T4
Solution heat treated and stabilised	TB7	-	-
Controlled cooling from casting and artificially aged or over aged	TE	T5	T5
Solution heat treated and fully artificially aged	TF	T6	T6
Solution heat treated and artificially underaged	-	-	T64
Solution heat treated and artificially overaged	-	T7	T7
Solution heat treated and artificially stabilised	TF7	-	-

lack of uniformity across castings. Other heating systems used are fluidized beds, superheated steam baths, oil baths, lead baths and salt baths [9,13,28,29].

2.5 The Microstructure and Alloy Modification

The microstructure of the A356 aluminium alloy depends mainly on its chemical composition, casting process, modification and heat treatment. Chemical composition determines concentration of constituents, intermetallic reactions and phases that will be observed. Figure 2.6 shows a typical microstructure of an A356 cast aluminium alloy. The silicon eutectic appears as sharp needle-like structures that are features of the unmodified alloy.

The casting process determines a cast's cooling rate and therefore size of constituents. A fast cooling process such as in pressure die casting produces fine eutectic structures, small dendritic cells, reduced arm spacing and smaller grain size. On the other hand a slower cooling process such as those of investment and sand casting result in much larger features [21,28]. In unmodified state an alloy is observed to have primary aluminium dendrites cells that are surrounded with a coarse eutectic phase distributed between dendrite arms. These phases appear as needles or plates with sharp sides and

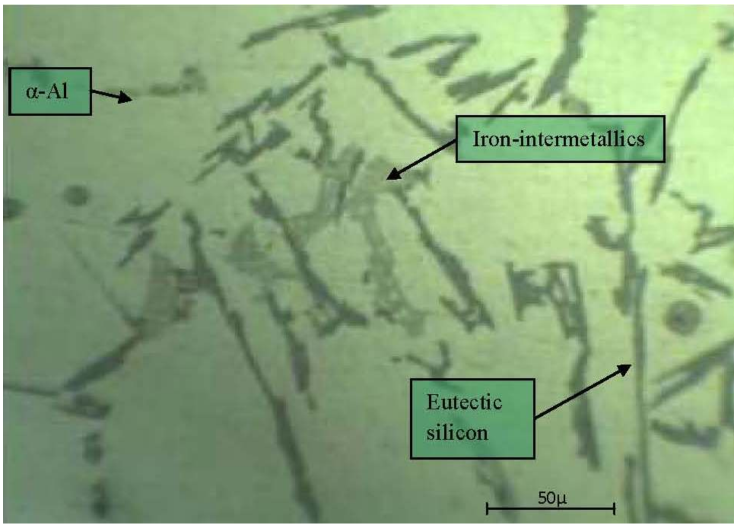


Figure 2.6: Primary aluminum matrix, needle structure of eutectic silicon and intermetallic phases in an A356 aluminium alloy in as cast state

ends and are termed as acicular silicon. When an alloy is treated with small amounts of strontium or sodium the eutectic phases are transformed to fine fibrous globular morphology. These transformations are referred to as modification and are responsible for the improved chemical properties associated with modified aluminum castings. Other chemicals that cause modification are potassium, rubidium, cerium, calcium, barium, lanthanum and ytterbium [12].

The choice of modifying element depends on factors such as ease of dissolution, vapor pressure of the melt, stability of the melt, secondary use and safety considerations. Sodium in elemental form is known to cause violent reactions, agitations and produces poisonous fumes. It is therefore added to the melt as fluxes of sodium fluoride that produce much less violent reactions or encapsulated in aluminum cans. Sodium has a low melting point of 98°C and therefore boils off immediately it enters the melt at between 760°C and 790°C, consequently its recovery is poor at between 20 to 30% [12].

Strontium is the most widely used modifier and is added to the melt either in the pure form or as a master alloy. Common master alloys for strontium modification are

Al-3.5%Sr, Al-10%Sr and the 90%Sr -10% Al. The modifier does not have violent reactions and has a recovery of up to 90%. Others are antimony, arsenic; selenium and cadmium. Antimony produces lamellar structures, is stable in melt and has nearly 100% recovery. However it is a toxic material and reacts with dissolved hydrogen to form stibine gas that is highly poisonous. Figure 2.7 shows an A356 aluminium alloys microstructure modified with Al-10%Sr [12].

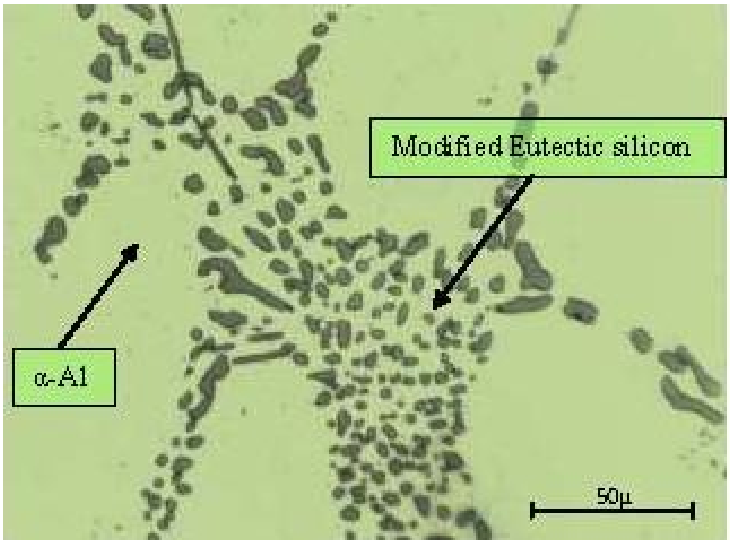


Figure 2.7: A356 aluminium alloy after modification with 0.02% Sr showing the fine fibrous nature of eutectic silicon

The modification of eutectic structure can also be achieved by other methods such as quench modification and super modification. In quench modification the fibrous eutectic structure is obtained by rapid solidification of the melt at growth rates of between 400 μm/s and 1000 μm/s. Super modification structural transformations are accomplished by heating the melt from the pouring temperatures (approximately 680°C) to between 850-900°C. The metal is held at that temperature for 15-30 minutes, cooled rapidly to pouring temperature and then cast. The method however requires the presence of magnesium in the alloy and therefore does not work for all alloys [25]. Another method involves application of high-intensity ultrasonic vibrations to an A356 aluminium alloy, this causes refinement of the eutectic silicon phase and modification of the microstructure [30] .

Heat treatment of aluminium alloys is also known to cause thermal degradation of eutectic silicon particles. When unmodified alloys are heat treated silicon plates disintegrate beginning at points of local defects in the crystal structure. These defects are morphological faults created during solidification process by terminations, holes, striations or fissures in the silicon plates. When the eutectic phases of modified alloys are exposed to heat they disintegrate and spheroidise faster than those of unmodified alloys. This is due to disturbances during modification that dispose the structures to thermal instability [31].

2.6 Aluminium Alloy Compositions

Aluminium alloys are broadly categorized as Al-Si-Mg based alloys, Al-Si-Cu based alloys or Al-Si-Cu-Mg based alloys based on the major alloying elements or by National specifications of major industrial nations such as the American Society for Testing and Materials (ASTM) and Japanese Industrial Standards (JIS)based on the elemental concentrations [7].

Irrespective of the mode of classification each alloy has a unique combination of the percentage concentrations of individual elements that orient it towards certain characteristics. This is achieved by the constitutive element interaction as certain material properties are improved while others are inadvertently diminished. Table 2.4 shows classifications of some aluminium alloy under this system.

When primary aluminium is obtained from the smelter it contains trace impurities of copper, manganese, nickel, zinc, tin, vanadium, sodium and galanium that are derived

Table 2.4: Chemical Compositions of Common Aluminium Alloys [32]

Alloy	**Elements(wt%)**					
	Si	Cu	Mg	Fe	Zn	Others
319	6.00	3.50	≤0.10	≤0.10	≤1.00	0.00
332	9.50	3.00	1.00	1.20	1.00	0.00
355	5.00	1.25	0.50	≤0.06	≤0.35	0.00
A356	7.00	≤0.20	0.35	≤0.20	≤0.10	0.00
A357	7.00	≤0.20	0.55	≤0.20	≤0.10	0.05 Be
380	8.50	3.50	≤0.10	≤1.30	≤3.00	0.00
383	10.00	2.50	0.10	1.30	3.00	0.15 Sn
384	11.00	2.00	≤0.30	≤1.30	≤1.00	0.35 Sn
390	17.00	4.50	0.55	≤1.30	≤0.10	≤0.10Mg
413	12.00	≤0.10	≤0.10	≤2.00	0.00	0.00
443	5.25	≤0.30	≤0.05	≤0.80	≤0.50	0.00

from the petroleum coke used in producing anodes and lining for the electrolytic cells. These elements are usually in amounts below 100 ppm (0.01%) and their influence on the metal is assumed to be negligible [12].

For foundry purposes, aluminium from the smelter is alloyed with other elements to exploit the benefits of the chemical interactions and improved castability.

Silicon is one of the most important alloying elements used as it increases fluidity, resistance to corrosion and helps the metal achieve good machinability. It also results in an alloy of low reduction in shrinkage during casting and low coefficient of thermal expansion. In essence silicon is the element that makes aluminium achieve its commercial viability in the casting industry [23]. In the automobile and aerospace industry, aluminium-silicon based alloys are the most extensively used because of their castability, good mechanical strength and resistance to wear [20].

Silicon forms a eutectic composition of 11.7% with aluminium at a temperature of 577°C. Alloys containing 10-13% silicon are thus classified as eutectic alloys and those containing with between 4-9% are hypoeutectic alloys. Those with silicon content above 13% are called hypereutectic alloys [14].

Eutectic alloys have the highest fluidity for a given casting temperature and are good for thin section casting. In the as-cast condition they are suited for applications where strength is not a criterion. Examples are in making of domestic cutlery, pump casings and manifolds. When they are heat treated however their strengths are highly elevated and they can be used for pistons, cylinders heads, and blocks for internal combustion engines of motor vehicles and farm implements [5].

Of the three classifications stated, hypoeutectic alloys are the most widely used and most preferred as secondary alloys. This is because they permit production of intricate designs with greater variations in section thickness and yield castings with higher surface finish. These properties favour manufacture of items requiring strength and high quality finish such as alloy wheels and cylinder heads [33]. In alloys containing between 3 and 5% silicon, hypoeutectic alloys are used in the as-cast condition to make rotors, fan blades and motor fittings while those with silicon content of less than 3% are used for marine fittings as they exhibit high resistance to saline corrosion [23].

Hypereutectic alloys on the other hand have high resistance to wear and abrasion and find application where these properties are a primary requirement. A common application is in the manufacture of diesel engine pistons and turbine blades. Their main drawback however is that they are difficult to machine [23].

Other elements used to alloy aluminium are copper, magnesium and iron. Copper is soluble up to a few percent in α-aluminium (5.65% in the binary alloy) and is a major constituent of intermetallic phases such as $AlCu_2$ (θ-phase) and $Al_7(FeCu)_2$. As an additive it improves tensile strength, machinability, thermal conductivity and is responsible for the increased hardness during heat treatment. However it is known to reduce resistance to hot tear, corrosion and fluidity [34].

Magnesium in concentrations of 0.25-0.45% improves the tensile strength of the alloy in the same way as copper. It forms magnesium silide (Mg_2Si) in the primary cells and subsequently precipitates to the grain boundaries causing the proof stress (PS) of the alloy to more than double. The presence of magnesium is useful in elevating technological parameters namely, the high strength to weight ratio and vibration dumping ability and therefore an important element in sports equipment and in the automotive industry [18].

Iron in aluminium is often associated with detrimental effects as it forms intermetallic phases. These phases are brittle in nature and when the material is loaded they promote initiation of cracks that deteriorate the alloys strength and ductility. When viewed under a microscope the intermetallic phases are observed to have varying morphology; appearing as plates Al_5FeSi, angular blocks $Al_{15}Fe_3Si_2$ or needle like β-Al_9FeSi [9].

For foundry purposes concentration of iron is maintained below 0.8% to limit negative effects on the cast's mechanical properties. In die castings however, the concentration may be raised to 1.1% to prevent the casting from sticking (soldering) on the die [8]. This is because when iron is alloyed in aluminium at above 0.8% the molten metal has little or no tendency to dissolve die steel when they are in contact. The higher iron content of the alloy reduces the solution potential for the die and casting machine parts. For this reason die cast alloys contain iron concentrations of between 0.8 and 1.1% [12].

In this study the aluminium alloy A356 was selected for short solution treatment because of its suitability as a secondary alloy, its relatively high fluidity in casting and its known favorable response to heat treatment. The alloy is also used in production of parts requiring high strength and is widely used by both small and large foundries [5,6].

2.7 Cooling in Aluminium-Silicon Alloys

In casting $AlSi_7Mg_{0.4}$, alloy cooling rate affects tensile strength properties and ductility directly [5]. Primarily it controls DAS whose influence on strength and ductility is absolute. When DAS is reduced, the alloys tensile properties and ductility are improved and when DAS is increased, lower values of the same are obtained [15].

In aluminium A356 alloys, cooling rate is used to control DAS and together with heat treatment manipulate tensile strengths and ductility. When the alloy is rapidly cooled and heat treated, tensile strengths and ductility are observed to be dramatically elevated. Controlling DAS and heat treatment allows the alloy to gain up to 90% in yield strength (YS), 91% ultimate tensile strength (UTS) and 87% ductility [15].

In determination of the effect of varying chemical modifiers (Strontium and Antimony) concentrations in aluminium A356 alloys having two different cooling rates (2.13°C/s and 0.95°C/s). It is established that up to an optimum modifier concentration, tensile, impact and fatigue properties are improved by higher margins in castings of faster cooling [17].

In these studies however effect of short heat treatment at shorter periods combined with effect of cooling rate on other material properties such as resistance to wear, abrasion and impact are not well established. These properties are important especially in the A356 Aluminium alloy which finds many applications as a primary and secondary alloy.

2.8 Short Cycle Solution Heat Treatment

As essential as heat treatment process is, it is usually associated with increased production costs and manufacturing bottlenecks. For instance an aluminum A356 alloy sand casting would undergo solution treatment at a temperature of 537°C ± 10°C for 6 - 12 hours, it would then be quenched in water at between 65°C - 100°C and artificially aged at 154°C ± 10°C for 2-5 hours as per T6 temper. Under T51 temper it would be age hardened at a temperature of 226°C ±10°C for 7 to 9 hours [31] leading to massive energy costs. A 65 kW - 415 volts three phase electric furnace of internal dimensions 800mm by 800mm by 1200mm typically used for heat treatment in foundries would consume 780 kWhs to run the T6 solution treatment process. At a rate of kshs. 5.75/unit charged by the Kenya Power Company it translates to about kshs. 4485.00. To run the T51 process it would consume 585 kWhs or Kshs. 3363.00. The heat treatment process therefore increases the total cost of production making it expensive to produce quality castings.

Various methods have been advanced towards reducing heat treatment time with varying degree of success. A fluidized bed system with advanced automation systems that increases efficiency in time and energy requirements during solution heat treatment has been developed resulting in higher heat transfer rates compared to conventional furnaces [9]. This system has a shorter heating time, better uniformity in heat transfer across parts and greater repeatability of the process. The system also has efficient thermal energy transfer to the process chamber (99% when using electric heating elements) [35]. These results in energy savings as fluid bed take about 4 minutes to reach the solutionising and aging temperatures while conventional furnaces reach the aging temperature in twice the time. The fluidized bed system nevertheless is highly automated with advanced control systems that require large capital investment [9].

Another method of shortening heat treatment is based on intrinsic manipulation of soluble phases in a material's microstructure. By increasing the maximum level of magnesium and silicon in α-aluminium phase, a short solution treatment of 30 minutes

will raise the tensile strength of a low pressure die cast A356 aluminium alloy to 90% of its maximum tensile strength. This however is limited to fulfillment of certain conditions; the alloy would be cast in a permanent die (or other method of rapid cooling) and the microstructure must be completely modified [15].
Both methods provided advances in feasibility of shortening heat treatment; the fluidized bed has high energy efficiency and is well suited for mass production but lacks flexibility and cannot be efficiently employed to small production runs. This reduces its feasibility in processes requiring small batches or use by small scale producers. As concerns the main requirement to reduce heat treatment time, the advanced fluidized bed fails to substantially reduce heating time.

Solute manipulation method offers better flexibility they offer and can be applied by both large and small scale producers. However this method has only been established in permanent mold castings and has not been determined in sand castings.

2.9 Summary

Sand castings by nature of their slow cooling are predisposed to poor mechanical properties compared to casting from methods of faster cooling such as permanent mold casting. They also represent a very important segment of the foundry industry as they account for 65% of all cast parts. This is because of the flexibility and relative lower investment requirements [5]. Parts made from sand casting can therefore benefit from a shortened heat treatment process. Studies conducted on effects of cooling rate and heat treatment have centered on individual effects of each parameter without consideration of cumulative effects that can be provided by consideration of both.

This study sought to determine effect of different cooling rates on aluminium alloy

A356 cast in sand mould as well as the effect of varying solution treatment time during heat treatment.

CHAPTER THREE

3.0 METHODOLOGY

3.1 Introduction

This chapter outlines the processes used in attaining the objectives of the study. The broad areas were the melting and casting processes, the heat treatment process, metallography and material testing.

3.2 The Melting and Casting Process

In the casting process there were three essential phases. The first involved selection and preparation of the base material, the second was the development of sand moulds incorporating thermocouples and the third phase was the actual melting and casting process.

3.2.1 Material Selection and Preparation

The materials used in this study were obtained from used motor vehicle aluminium wheels. These were broken down to allow them to fit into an oil fired furnace and melted under a cover flux at the JKUAT foundry. When the melt attained a temperature of 730°C, it was tapped, skimmed off and poured into moulds fabricated with mild steel to make 5 kg ingots. These were allowed to cool and were weighed to establish their exact masses. For chemical composition analysis a small amount of the melt was collected in a copper crucible and quenched rapidly in water to avoid composition segregation. This sample was analysed using the Meta Vision Spectrometer and the elemental composition determined.

3.2.2 Mould Assembly

The mould was made using fine sea sand mixed with 3% sodium silicate and hardened with CO_2 gas. The mold cavity was of dimensions 150 mm by 130 mm by 20 mm with one of the walls consisting of the cast iron chill [Appendix **A** and **B**]. Four k-type thermocouples connected to a digital data logger were then assembled in the moulds at distances of 27 mm from each other with first one 22 mm from the chill (Figure 3.1).

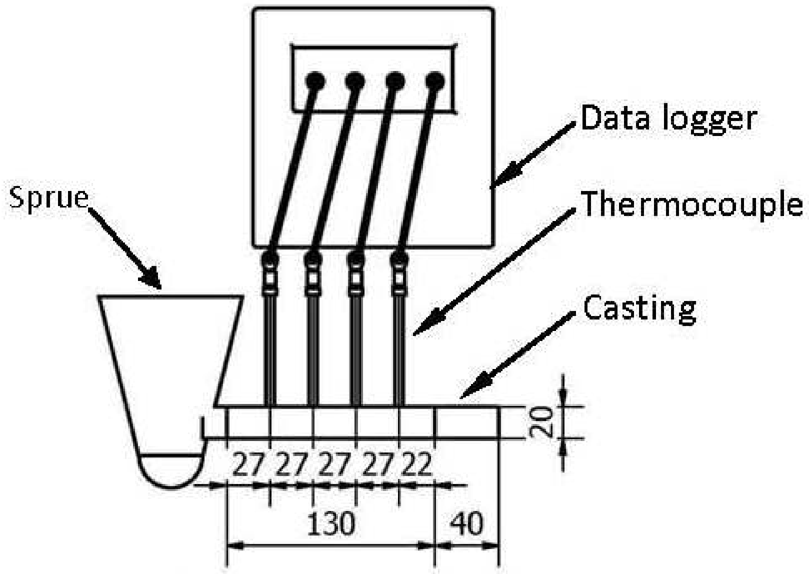


Figure 3.1: The casting assembly

3.2.3 Melting and Casting

Ingots of 5 kgs each were charged in a graphite crucible and melted under a coverall flux in an electric muffle furnace to a temperature of 750^0C. Upon reaching this temperature the melt was treated with an aluminium-strontium master alloy and a C-19 Nitral degasser. The addition of the master alloy preceded the degasser and the amount was calculated to bring the strontium concentration in the melt to 0.02% wt.. The mixture was then stirred gently and continuously for 5 minutes to ensure homogeneous dissolution of the master alloy.

Prior to pouring, a degasser constituting 0.4% weight of the ingot was added to the melt and held until the gas bubbling action ceased. The liquid metal was then skimmed off the slug and poured into the sand moulds at a temperature of 720°C.

At this time the thermocouples captured the temperatures of the cooling metal while the digital data logger recorded these values at intervals of 5 seconds. After the cooling stopped the mould was broken, the casting, the sprue and the thermocouple probes isolated. The casting was then brushed lightly and cleaned to rid sand particles and any other dirt.

3.3 The Heat Treatment Process

Heat treatment was carried out on specimen that had been cut from sections of the casting that had undergone preliminary machining for impact testing, tensile testing and microstructure analysis. The treatment process was carried out in three stages; the first was in an electric muffle furnace, the second in preheated water and the third in a hot air oven. In the first stage the muffle furnace was maintained at a temperature of 540°C and four sets of the test pieces were heated in the furnace for varying periods.

The first set was heat treated for 30 minutes, the second for 1 hour, the third for 3 hours and the fourth for 6 hours. The fifth set was retained in the as-cast condition to provide reference that would help determine the degree of change resulting from the heat treatment process.

The second procedure involved rapidly withdrawing the test specimens from the furnace after the predetermined period and quenching in water held at 60°C. This procedure lasted a few seconds and led to the third procedure where the specimens were heated albeit at a lower temperature of 170°C for 3 hours in the hot air oven. The specimens were then left to cool naturally and tested with the relevant equipment.

3.4 Metallographic Preparations

Preparation of the specimens for microstructure analysis commenced by filing the surface of the specimens to eliminate mechanical distortions produced by cutting and to provide the initial flat surface. Care was taken to avoid over heating by intermittently dipping the specimens in water during the process. To remove the filing marks, abrasive smoothing was done using SiC papers of 280 grit, 400 grit and 600 grit successively. However, scratch marks were visible and a 0.25 μm diamond paste was used to polish off the scratches and bring the surface to a near mirror image.

For the microstructure to be revealed, the specimen had to be etched. Keller's reagent was selected as a suitable etchant and was prepared by mixing hydrofluoric acid, hydrochloric acid and nitric acid before it was made up with distilled water. The specimens were then dipped in the reagent for 20 seconds, flashed with methanol spray and dried with a hot air blower. An optical microscope (OPTIKA 353 MET) was then used to take micrographs the specimens that were analysed using the Microstructure

Characterizer (MIC 3.0).

3.5 Material Testing

3.5.1 Tensile Testing

Tensile tests were carried out using a Hounsfield Tensometer located at the University of Nairobi materials workshop. The test specimen were machined to a gauge length of 25.4 mm and gauge diameter of 6.35 mm as per ASTM B557-02a [27]. The specimens were marked and mounted on the tensometer from where they were strained at a rate of 3mm/minute until they failed. The test pieces were then assembled and the new gauge length taken to determine the elongation of the test piece. The maximum load at fracture was obtained from a mercury scale on the equipment and recorded along with the strains. Appendix **C** shows the design dimensions of the tensile test piece.

3.5.2 Impact Testing

The Impact test pieces were unnotched specimen of dimensions 55 mm by 10 mm by 10 mm, as shown in Figure 3.2. These were machined from specifications of the test standard ASTM E-23 [36]. Tests for impact resistance were carried out at the JKUAT mechanical science laboratory using the Torsee's Charpy Impact testing machine having a hammer of 25.71 kg, arm length of 750 mm and a swing angle of 142.5^o.

The test began by positioning the work piece on the anvil, setting the energy indicator at the maximum scale reading and releasing the pendulum from the latch position. The absorbed energy was obtained by getting the difference between the lift angle and the swing angle and applying them in Equation 3.1. Each test set had six specimens and the average energy value recorded from the specimens recorded as the impact energy.

$$E = PD(\cos\alpha - \cos\beta) \tag{3.1}$$

Where, α is the lift angle, β the swing angle, P the total weight (25.710 kg) and D the distance from the center of the revolving axis to center of gravity (0.650 m).

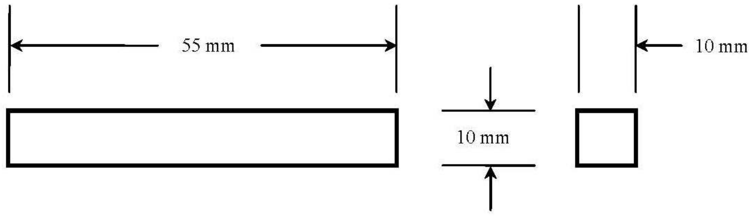


Figure 3.2: Dimensions of the impact test specimen

3.5.3 Hardness Testing

Hardness testing was carried out using the optical Macro Vickers Hardness Testing machine, LV 800 at the Materials Department of University of Nairobi. The specimens were cut to dimensions of 24 mm by 24 mm by 24 mm and then prepared to metallographic standards specified in ASTM E-8M [37] as the machine could only work by microstructural visualization.

The specimens were mounted on the work piece holder and automatically indented under a test load of 3 kg-f and for a dwell period of 10 seconds. Figure 3.3 shows the indenter with a square-based pyramidal diamond having face angles of 136° while Figure 3.4 shows the impression made on a flat surface.

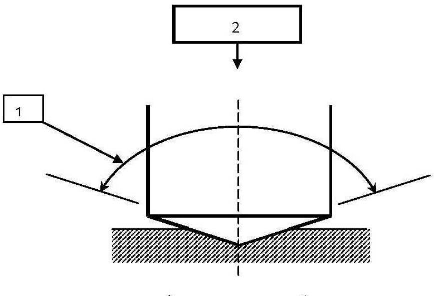


Figure 3.3: Hardness testing pyramid indenter [3].

where

1 denotes the Angle of vertex of the pyramidal indenter 136° and

2 denotes the Test load in kilogram-force

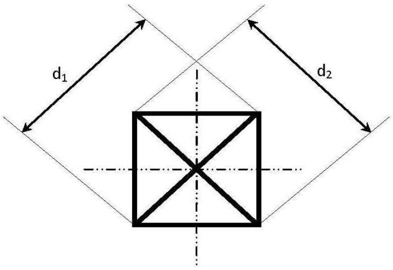


Figure 3.4: Impression made on a flat surface by the pyramid indenter [3].

Where d_1 and d_2 are the major diagonals of the indentation.

When the indenter was removed, a microscope was used to capture the dimensions of the impressions on the work piece by moving lines of the ocular lens between the diagonals (d_1 and d_2). A software then processed these readings and posted the hardness values on a display console. For each specimen ten randomly distributed indentations were made and the average value taken as the true Vickers hardness.

3.6 The Industrial Foundry Survey

The survey was conducted to determine challenges faced by foundries in Kenya and suggest possible remedial action. It was conducted within geographical areas of Kisumu town, Nakuru town, Nairobi and Thika town. The study initially targeted forty five foundry establishments but only managed twenty. This was because some outlets had closed, relocated, changed practice or could not be permitted.

The study was guided by a questionnaire (Appendix D) having two sections: The first section sought to identify and categorize foundry establishments based on location and number of employees. The second section formed the bulk of the study and focused on matters related to scrap; sources of scrap metal, scrap selection methods, melting and melts treatment. The section also tried to ascertain the challenges faced by foundries and possible remedies. Others were products manufactured, quality control practices, casting methods and equipment, educational backgrounds and training (both formal and informal).

CHAPTER FOUR

4.0 RESULTS AND DISCUSSION

4.1 Chemical Composition Analysis

4.1.1 Results

Table 4.1 shows results of the chemical composition analysis obtained for the casting material. Also presented are equivalent alloy composition limits used to classify the same aluminium alloy series. These are the British Standards (BS), American Society for Testing and Materials (ASTM) and Japanese System (JIS).

Table 4.1: Chemical composition analysis (in wt %) of the test piece along with other comparative classification standards. [32]

		Alloy Elements (wt %)						
		Si	Mg	Fe	Cu	Mn	Be	Ti
Alloy Testpiece		6.92	0.356	0.116	≤0.05	≤0.02	0.001	0.148
Equivalent	**LM 25**	6.5-7.5	0.2 -0.6	≤0.5	0.2	≤0.3	≤0.05	≤0.2
	A356	7.0	0.35	≤ 0.2	≤ 0.2	-	-	-
	AC 4C	6.5-7.5	0.20-0.45	≤ 0.2	≤ 0.1	≤0.1	-	≤0.2

4.1.2 Discussion

From the composition results of Table 4.1 the casting material was determined to be A356 according to ASTM B 26/B 26M [32]. Other equivalent classifications were LM 25 according to the BS standards and AC 4C according to Japanese standards.

4.2 The Cooling Rate

Temperatures across the casting were read by thermocouples and recorded by a digital data logger. This was carried out at intervals of five seconds beginning from the time the metal was poured into the sand mold cavity to the time the casting was completely cooled.

4.2.1 Results

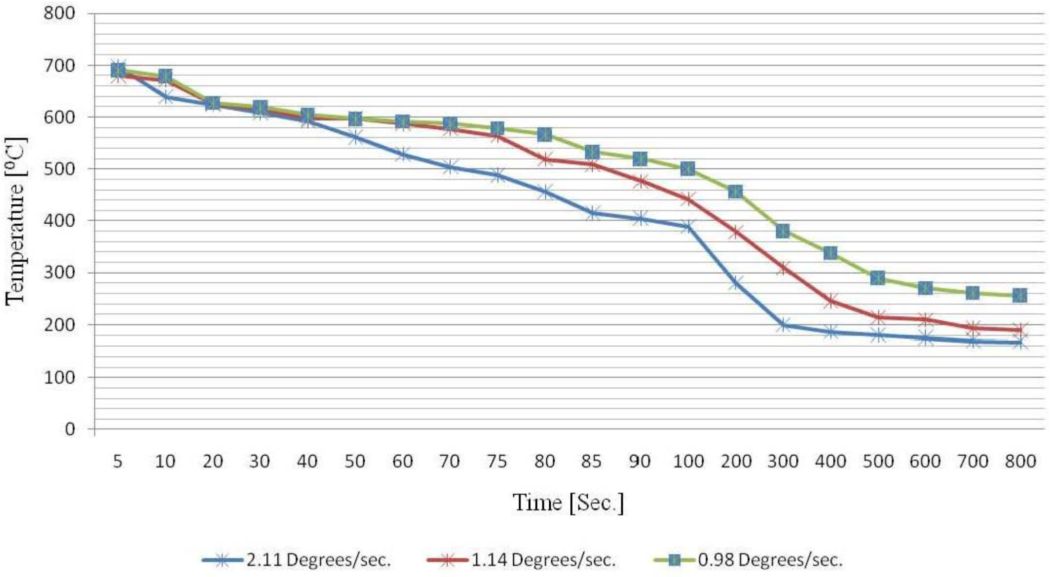


Figure 4.1: Trends in cooling across the casting

Figure 4.1 (and data in Appendix **E**) show the relationship between temperature and time recorded by the data logger.

The sections between thermocouples points had distinct cooling rates that were determined from the time crystals of the metal began forming to the time all liquid metal had turned to solid. In aluminium A356 alloys, solidification begins at 625°C and ends at 564°C.

The casting was cut along these points and individual sections isolated as shown in Figure 4.2. The first piece was adjacent to the chill (section I) and was determined to have a cooling rate of 2.11°C/s (between 625.3°C at 20 s and 562.1°C/s at 50 s) based on the output collected from the data logger. The second piece from the chill (section II) had a cooling rate of 1.14°C/s (between 626.6°C at 20s and 563.9°C at 75s) while the third piece which was farthest from the chill (section III) and had a cooling rate of 0.98°C/s (627.7°C at 20s and 566.5°C at 80s).

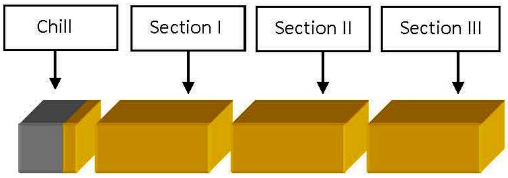


Figure 4.2: The cut-off sections of the casting representing areas of distinct cooling rate

4.2.2 Discussion

By application of a chill at the inner end of one of the mold cavity walls and a riser on the opposite end, there was a temperature gradient across the casting as it cooled. Section I cooled fastest because it was adjacent to the chill that had a high heat conductivity compared to the surrounding sand mold.

Section II cooled slower than section I but faster than section III. This again was attributed to the fact that the former was closer to the chill while the latter was furthest from the chill and its proximity to the sprue reduced its ability to dissipate heat to its surrounding as fast other sections.

4.3 The Secondary Dendrite Arm Spacing

4.3.1 Results

SDAS was obtained by analysis of micrographs of sections I, II and III in as-cast state. An image characterizer software was used to facilitate application of the point count method to analyze microstructure fields and determine the dendrite spacing's. Readings from each field were recorded and the average SDAS of section I, II and III determined to be 31μm, 37μm and 40μm respectively as shown in Figure 4.3 and Table F.1 of Appendix **F**.

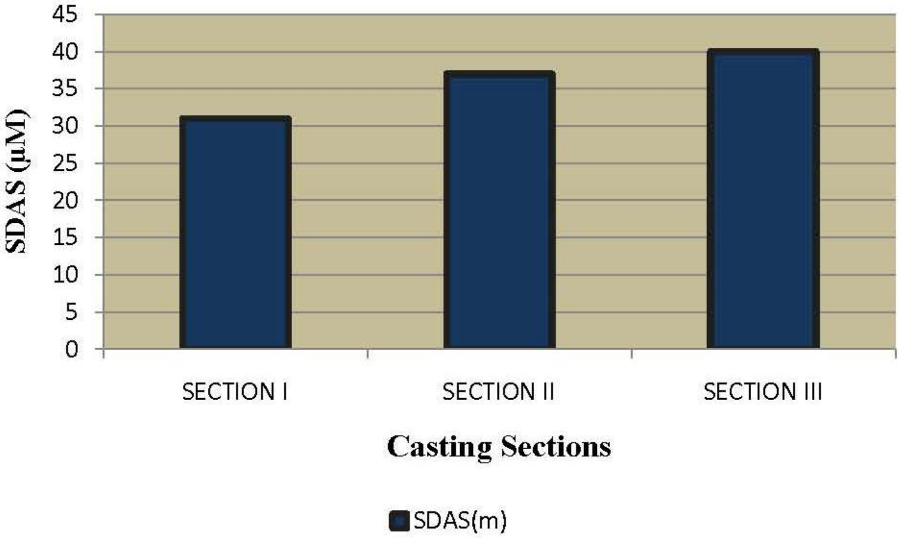


Figure 4.3: SDAS obtained at each section of the casting.

4.3.2 Discussion

The sizes of SDAS in an aluminium alloy casting are directly related to rate of cooling. Smaller dendrites and therefore smaller dendrite spaces are formed when a casting cools

rapidly. This is because finer networks serve as more efficient conductors of latent heat to the undercooled liquid [1].
Since section I had the fastest cooling rate it formed smaller dendrites and arm spaces compared to those of sections II. Similarly section II had smaller dendrite and arm spacing than those of section III.

4.4 Grain Size Analysis

4.4.1 Results

ASTM Grain Size Numbers for sections I, II and III were obtained by image analyses of respective sections in as-cast state. Specimens were prepared to metallographic specification ASTM 0003-01 [37], viewed under an optical microscope and micrographs captured at magnifications of 100 by a digital camera. These were then processed by image characterizer software that determined the Grain Size Numbers of sections I, II and III to be 12.951, 12.264 and 11.175 respectively. Figure 4.4, 4.5 and 4.6 shows grain intercepts and Grain Size Numbers in sections I, II and III respectively.

4.4.2 Discussion

Section I had the largest Grain Size Number of 12.951 that according to Equation 2.5 translated to approximately 3959 grains per square inch (see conversion table in Appendix G.1 [4]). Sections II and III had 12.264 and 11.175 that translated to 2459 and 1156 grains per square inch respectively.

In any casting the numbers of grains are primarily influenced by the alloy's chemical composition and rate of cooling during solidification [5]. Since chemical compositions of

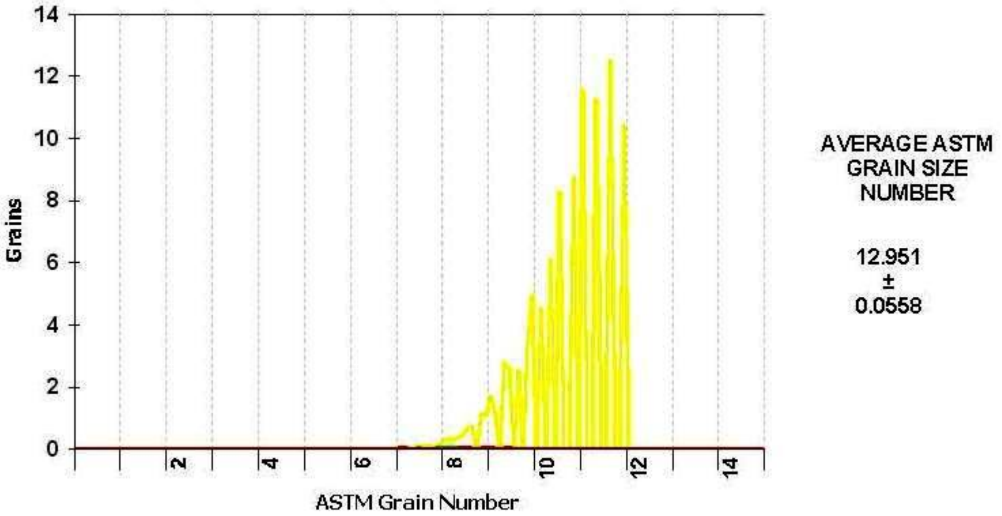


Figure 4.4: Grain Size Analysis of section I

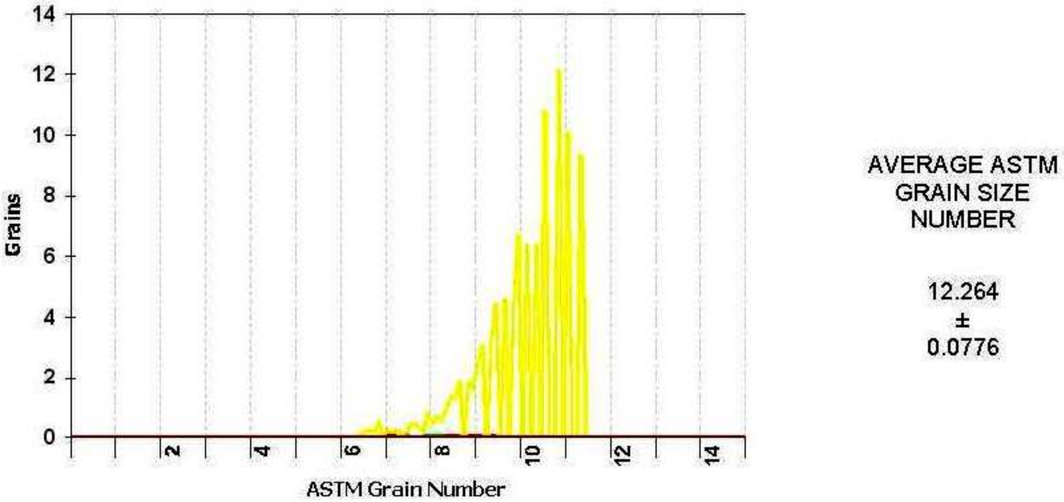


Figure 4.5: Grain Size Analysis of section II

the sections I, II and III are similar, the difference in grain count can only be attributed to dynamics that affect the cooling process.

Section I was nearest to the chill therefore cooled faster and ensured that during solidification, the degree of nucleation and growth of cells at this region was greatest. The result was a rapid formation of cells with terminated growth and hence a large number

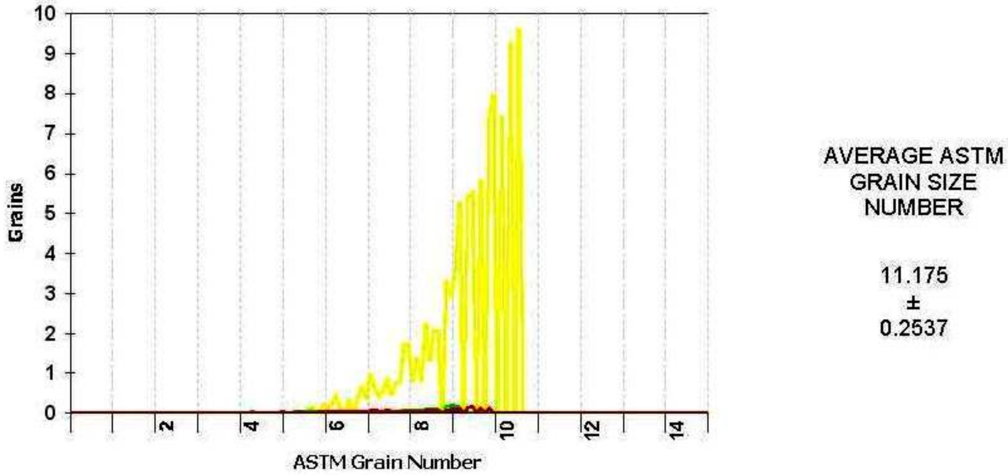


Figure 4.6: Grain Size Analysis of section III

of smaller finely dispersed grains [1].

The rate of cooling in section II was intermediate to section I and III and this was reflected in the number of grains formed. This section formed fewer grains than section I but had more than those of section III per unit area.

Section III was farthest from the chill and nearest to the riser. It therefore recorded the slowest cooling and the effect was slower nucleation and growth of primary cells leading to fewer grains per unit area. These results corroborate findings in DAS as sections with smaller SDAS correspond to formation of smaller grains and vice versa.

4.5 The Cast Microstructure

4.5.1 Results

Figures 4.7 (a), (b), (c), (d), and (e) show micrographs of the section having a cooling rate of 2.11°C/s. Figure 4.7 (a) shows the micrograph in the as-cast state and had therefore undergone neither solution heat treatment nor precipitation hardening process. Figures 4.7 (b), (c), (d) and (e) shows micrographs after solution heat treated for periods of 30 minutes, 1 hour, 3 hours and 6 hours respectively; after solutionising all samples were quenched in water at 60°C and aged for 3 hours at 170°C.

Micrographs in Figures 4.8(a), (b), (c), (d), and (e) are from the section having a cooling rate of 1.14°C/s. Figure 4.8 (a) shows the as-cast state while Figures 4.8 (b), (c), (d) and (e) shows micrographs after solution heat treatment for 30 minutes, 1 hour, 3 hours and 6 hours respectively.

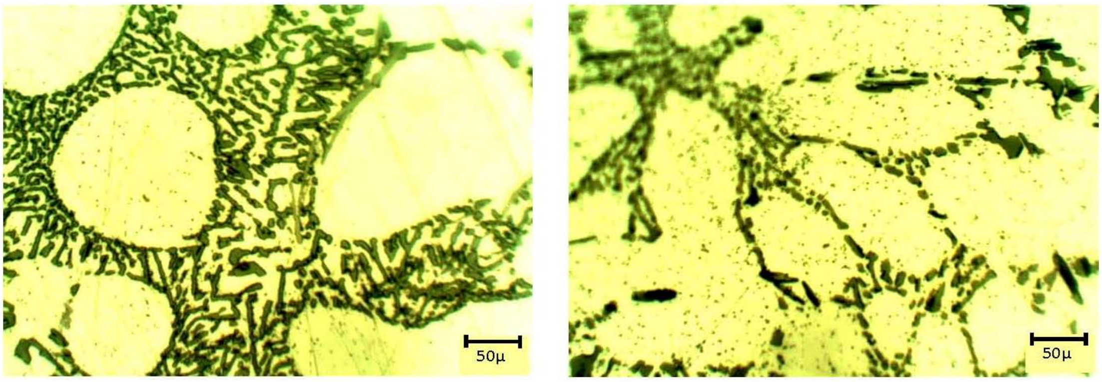
Micrographs in Figures 4.9 (a), (b), (c), (d), and (e) are from the section having a cooling rate of 0.98°C/s. Figure 4.9 (a) shows the micrograph in the as cast state while Figures 4.9 (b), (c), (d), and (e) show the micrographs after solution treated for 30 minutes, 1 hour, 3 hours and 6 hours respectively.

4.5.2 Discussion

The microstructures of section I in Figure 4.7 are observed to be similar to those of a typical hypoeutectic aluminium alloy with primary α-aluminium dendrites being the predominant phase surrounded by regions of irregular Al-Si eutectic. The eutectic forms a network of fine fibrous particles around the primary phase which is a feature of modification in aluminium alloys [17, 25].

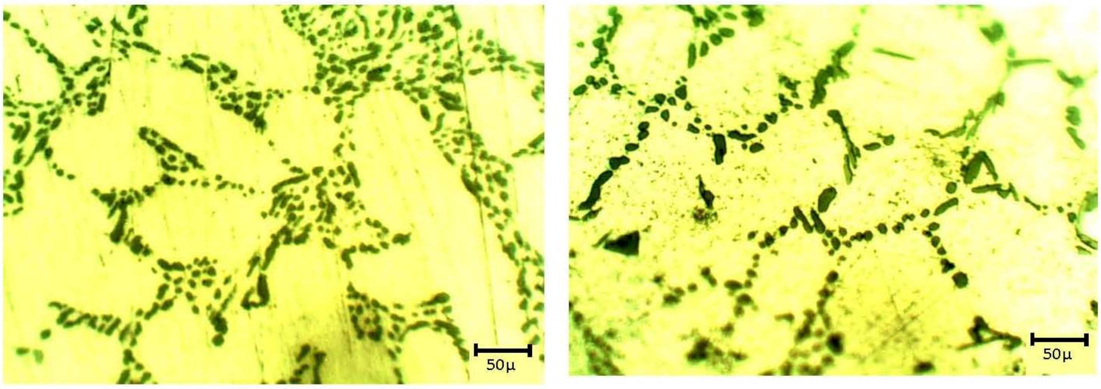
From Figure 4.7 (b) and (c) the effect of heat treatment is clear as eutectic silicon fibres are fragmented and silicon particles observed to have spheroidised. This is also the case in Figure 4.7 (d) with silicon particles appearing even coarser and spacing between them even larger.

Figure 4.7 (e) shows the consequence of prolonged solution treatment (6 hours) as there



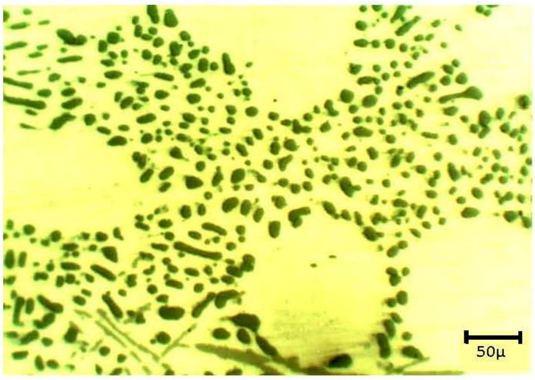
(a) As-cast

(b) After 30 Minutes Solution Treatment



(c) After 1 Hour Solution Treatment

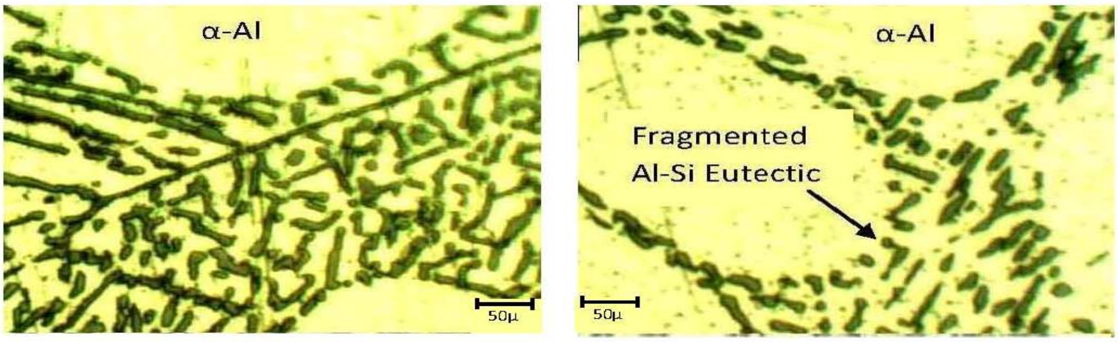
(d) After 3 Hour Solution Treatment



(e) After 6 Hour Solution Treatment

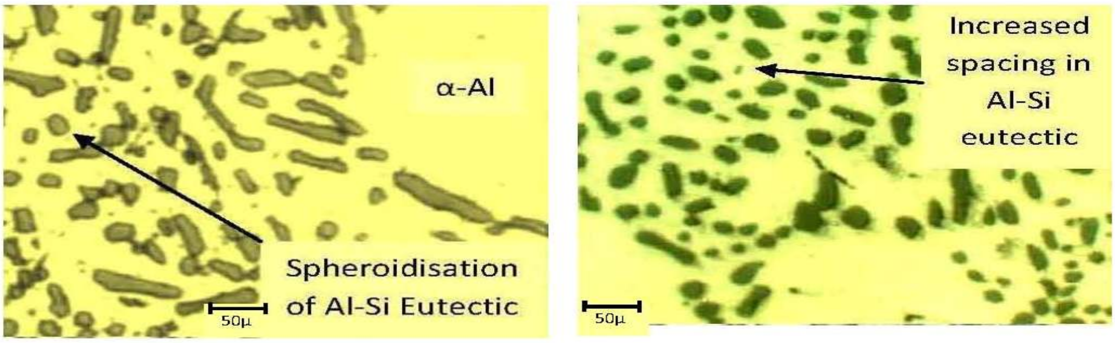
Figure 4.7: Microstructures of section I in the as-cast condition (a) after solution treatment for 30 minutes (b)1 hour (c) 3 hours (d) and 6 hours (e).

is discernible growth of eutectic silicon particles and significant increase in spacing between them.



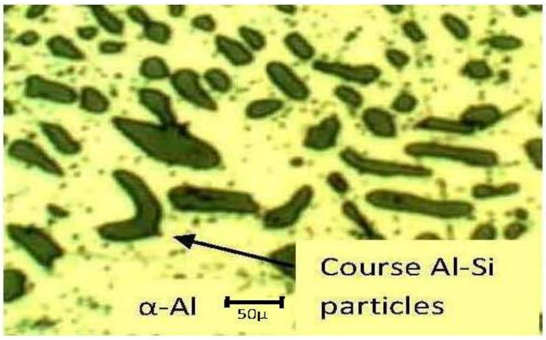
(a) As-cast

(b) After 30 Minutes Solution Treatment



(c) After 1 Hour Solution Treatment

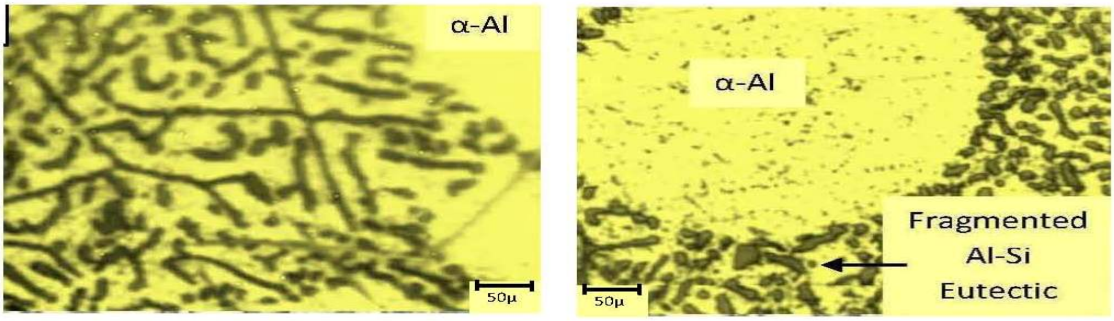
(d) After 3 Hour Solution Treatment



(e) After 6 Hour Solution Treatment

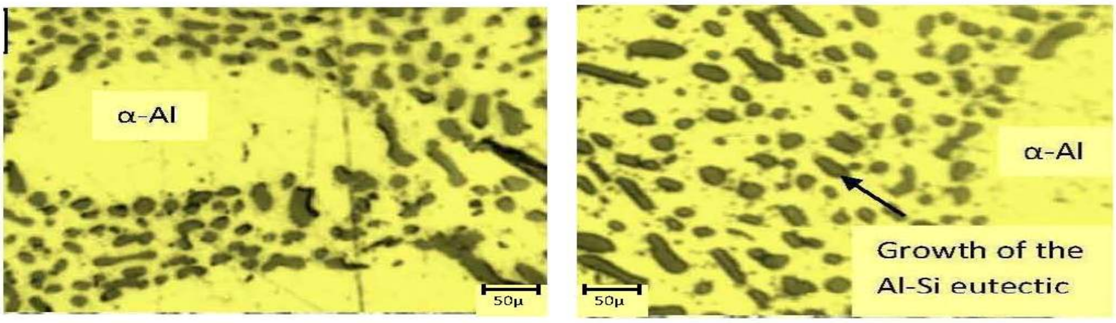
Figure 4.8: Microstructures of section II in the as-cast condition (a) after solution treatment for 30 minutes (b)1 hour (c) 3 hours (d) and 6 hours (e)

These changes in morphology after heat treatment are a well established occurrence as fibrous silicon phases of modified structures are known to fragment and spheroidise more rapidly than plate shaped silicon particles in the unmodified structure. Solution treatment of an unmodified aluminium alloy for 2 hours has negligible effect on the morphology of silicon particles. However when the microstructure is fully modified



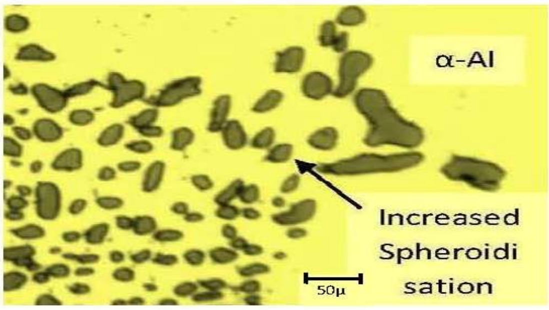
(a) As-cast

(b) After 30 Minutes Solution Treatment



(c) After 1 Hour Solution Treatment

(d) After 3 Hour Solution Treatment



(e) After 6 Hour Solution Treatment

Figure 4.9: Microstructures of section III in the as-cast condition (a) after solution treatment for 30 minutes (b)1 hour (c) 3 hours (d) and 6 hours (e)

there is significant change in the morphology. The micrographs in Figures 4.7 (b), (c), (d) and (e) agree with this observation as after 30 minutes solution treatment silicon particles are noted to spheroidise. However on solution treatment for longer periods of 1 hour, 3 hours and 6 hours, therse is no further increase in spheroidisation [5].

In the micrographs of section II (Figure 4.8) the expected constituent elements: primary

α-aluminium dendrites and eutectic silicon phase are clearly visible. When sections I and II are compared, primary dendrites in section I appear to be smaller than those of section II and have a finer network that is visually more closely cropped.

When specimens in section II are solution treated for 30 minutes and 1 hour (Figure 4.8 (b) and (c)) eutectic silicon particles are observed to have progressively fragmented, spheroidised and coarsened. At longer solution heat treatment periods of 3 hours, (Figure 4.8 (d)) and 6 hours, (Figure 4.8 (e)) silicon particles are noted to have gained in size and distance between them even greater.

Figure 4.9 (a) shows the micrograph of the section having a cooling rate of 0.98°C/s in as-cast state and shows the clear effects of a slow cooling process. When micrographs of this section are compared visually to sections I and II (Figure 4.7 and Figure 4.8), primary dendrites in this section appear to be bigger. In Figure 4.9 (b), eutectic particles are observed to fragment after 30 minutes of solution treatment but are not fully spheroidised. Figure 4.9 (c) shows partial spheroidisation of eutectic silicon but no coarsening of silicon particles as observed in micrographs of sections of faster cooling rates. At a longer solution treatment time of 3 hours, a mixture of silicon particles are observed, some of which are partially spheroidised and others fully spheroidised (Figure 4.9 (d)). In Figure 4.9 (e), a large degree of eutectic silicon particles appear to have spheroidised with a mix of elements that are not completely spheroidised.

Microstructures of castings produced from thin wall molds, permanent molds or molds resulting in fast cooling are generally finer than those produced in thicker sand molds even after heat treatment and are known to undergo changes in shape and size during heat treatment [8, 22].

The changes occurring in the microstructure of section III were typical of a slow cooling casting or a sand casting of large volume. The slow spheroidisation process predisposes them to poor mechanical properties and low response to heat treatment.

4.6 Tensile Tests

4.6.1 Results

Figure 4.10, 4.11 and 4.12 (also Table H.1, Figure H.1,Figure H.2 and Figure H.3 in Appendix **H**) show YS and UTS values of sections I, II and III in as-cast state and after solution treatment for 30 minutes, 1 hour, 3 hours and 6 hours. Figure 4.10 shows that the YS and UTS of section I in as-cast state are 118 MPa and 168 MPa respectively. After 30 minutes, 1 hour and 3 hours of solution treatment YS increases by 86%, 87% and 98% to 220 MPa, 221 MPa and 234 MPa respectively. Over the same period UTS increases by 40%, 51% and 57% to 236 MPa, 253 MPa and 264 MPa respectively. Further solution treatment of 6 hours shows highest strengths as YS increases by 103% to 239 MPa and UTS by 61% to 270 MPa. From Figure 4.11 YS in

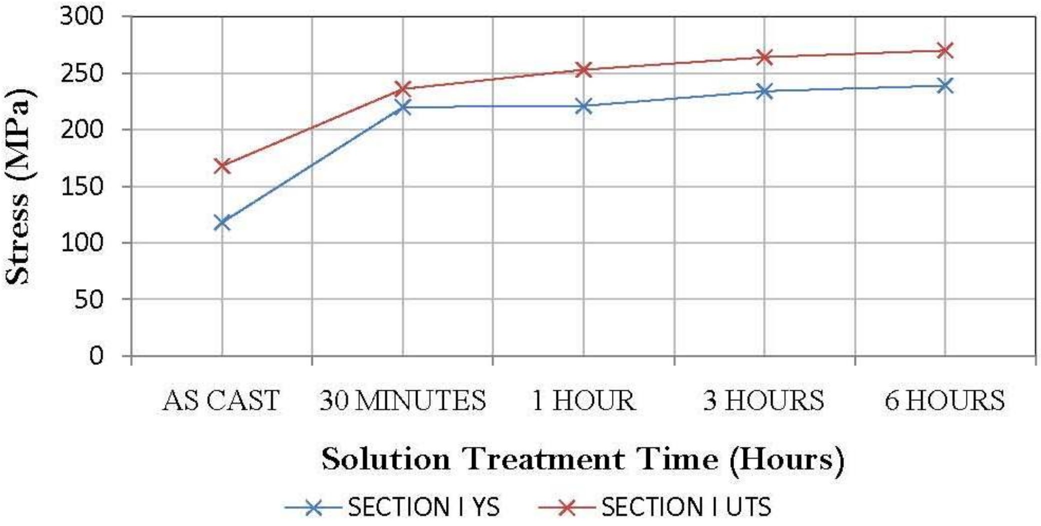


Figure 4.10: Yield stress and ultimate tensile strength of Section I

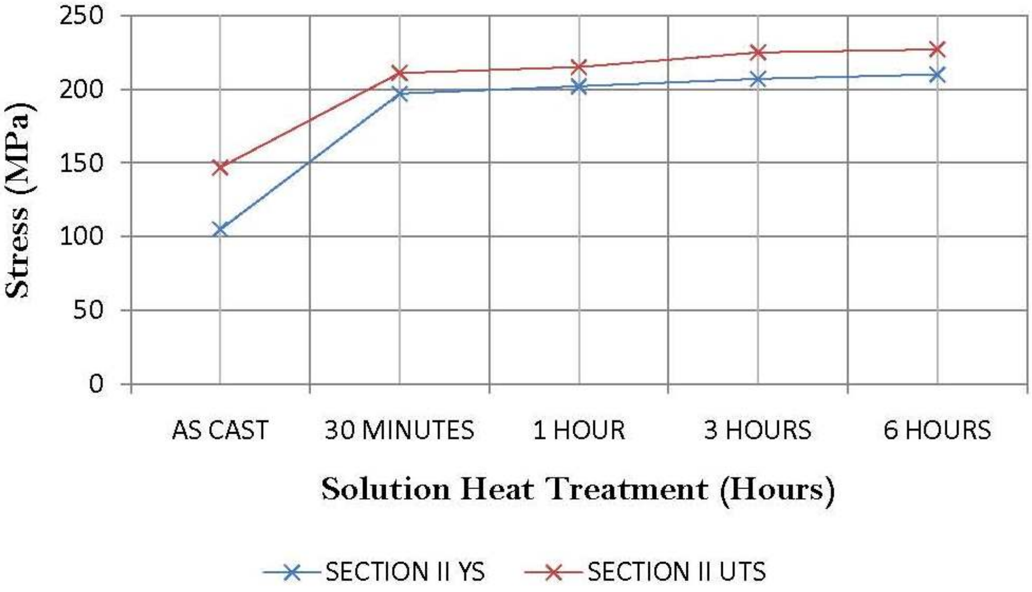


Figure 4.11: Yield stress and ultimate tensile strength of section II

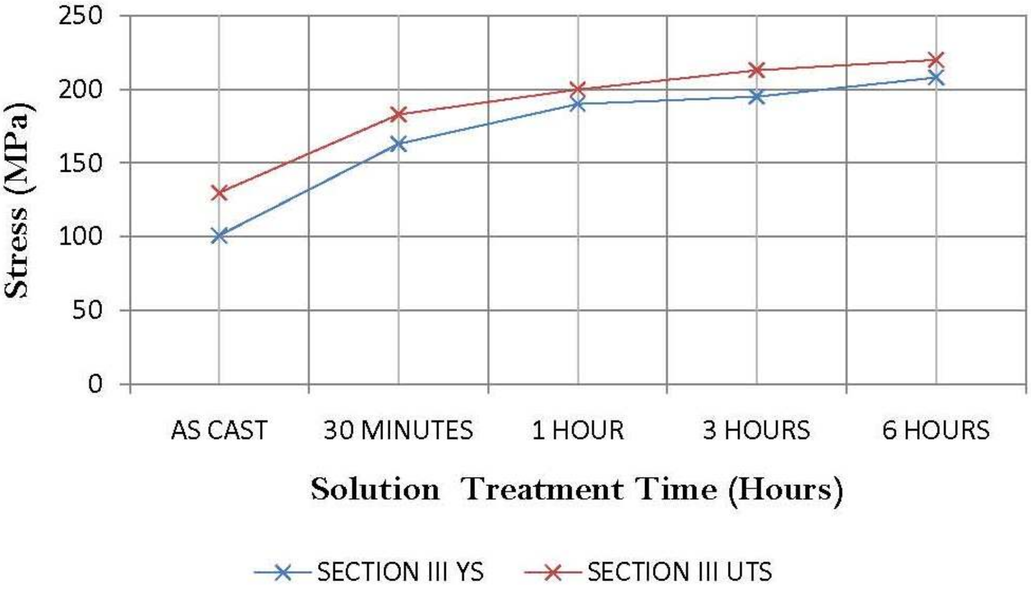


Figure 4.12: Yield stress and ultimate tensile strength of section III

as-cast state is 105 MPa while UTS is 147 MPa. When solution treatment is applied for 30 minutes, 1 hour and 3 hours; YS increases by 87%, 92% and 97% to 197 MPa, 202 MPa and 207 MPa respectively. UTS also has similar gains as it increases by 44%

to 197 MPa after 30 minutes, 46% to 202 MPa after 1 hour and 53% to 207 MPa after 3 hours. When solution time is extended to 6 hours, maximum strength values are observed as YS increases by 100% to 210 MPa and UTS by 54% to 227 MPa.

In section III (Figure 4.12) YS in as-cast state are 101 MPa and the corresponding UTS are 130 MPa. After solution treatment for 30 minutes, 1 hour, 3 hours and 6 hours YS increases to 163MPa, 190 MPa, 195 MPa and 208 MPa while UTS increases to 183 MPa, 200 MPa, 213 MPa and 220 MPa respectively.

4.6.2 Discussion

From Figures 4.10, 4.11 and 4.12, effects of cooling and heat treatment on tensile properties of various casting sections is evident. Section I has consistently better YS and UTS when compared to sections II and III both in as-cast state and heat treated condition. These observations are attributed to grain sizes and SDAS occasioned by varying cooling rate across the casting. Increased grain boundaries in section I impede ease with which slip or dislocations traverse across the grain cells [19]. This means section I with larger grain boundary density is better at restricting mobility of dislocations and a greater mechanical force is required to initiate plastic deformation. Another effect of the large number of grains is increased imperfections in the lattice structure. Grain boundaries increase imperfections in a materials lattice structure which also raises tensile strengths. Section I therefore has higher tensile strengths than sections II. Section II has more grains than section III and also better tensile strengths.

SDAS also explains better strengths recorded in section I compared to sections II and III. It is observed that when SDAS is reduced, a cast alloys mechanical properties are invariably improved. This is attributed to residual Hall-Petch hardening effect and restricted growth and nucleation of inter dendritic phases [5]. Section I being nearest to the chill has smaller SDAS because of fast nucleation and terminated growth of dendrite cells. Specimens in section I therefore have better tensile strengths than section II; and those of Section II better than those of section III.

The effect of heat treatment is observed when specimens from all sections are solution treated for 30 minutes, 1 hour, 3 hours and 6 hours. Figure 4.10, 4.11 and 4.12 show that with heat treatment tensile strengths increase remarkably from as-cast state. This is because when an aluminium alloy is heated at just below its solidus temperature the solute solubility limit is raised and there is formation of fine β-phase precipitates that strengthen the primary aluminium matrix [6]. These β-phase constituents go into solid solution with aluminium matrix resulting in super saturated solid solutions; the result is observed in increase of YS.

It is also observed that cooling rate and solution treatment time play significant roles in determination of tensile strengths. In section I of faster cooling, tensile strengths is higher after 30 minutes of solution treatment compared to sections II and III. However even at section III of lowest cooling rate increase in YS and UTS (61% and 31% respectively) is quite significant compared to as cast state.

4.7 Hardness

4.7.1 Results

Figure 4.13 and Table H.2 in Appendix **H** show Vickers hardness values obtained in sections I, II and III in as-cast state and after heat treatment. In as-cast state, Vickers hardness value of sections I, II and III are 60, 54 and 58 respectively. After solution heat treatment of 30 minutes, 1 hour, 3 hours and 6 hours, hardness values in section I are observed to increase by 18%, 13%, 13% and 3% respectively. In section II increase is by 17%, 7%, 7% and 13% over the same period and 14%, 14%, 16% and 16% in section III.

4.7.2 Discussion

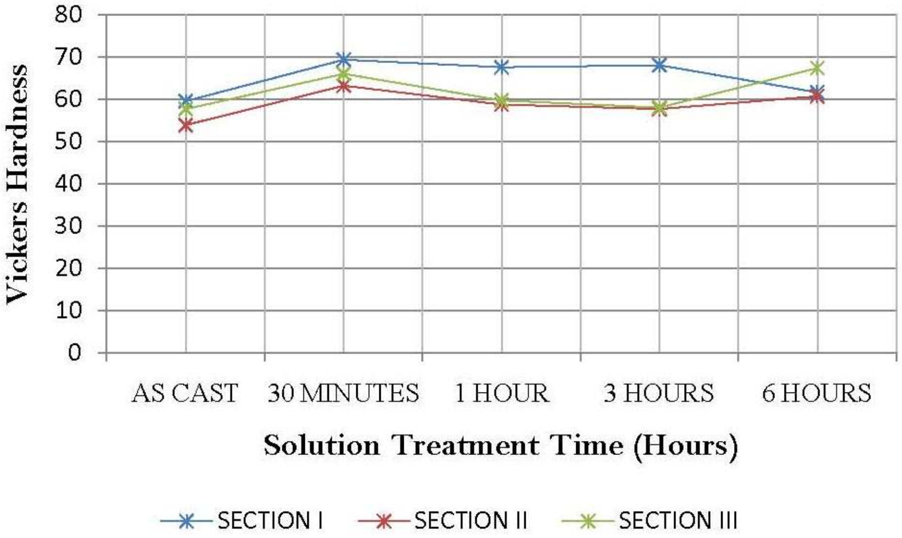


Figure 4.13: Trends in hardness in Sections I, II and III

From Figure 4.13 hardness values recorded in sections I, II and III in as-cast state are observed to be lower than those of corresponding sections subjected to heat treatment. This is explained by the fact that when an aluminum alloy is heat treated, solutes are formed during solution heat treatment stage and trapped within the matrix by quenching. At the time of aging these solutes precipitate and lie in planes along boundaries.

Copper in particular forms metallic compounds ($CuAl_2$) with the matrix within the cells crystal structure and precipitate along the planes of individual cells. These deposits resist deformation and sliding motion along planes of cells boundaries and hence the metal is hardened. Dissolution of solutes is accomplished at high temperatures and as observed in Figure 4.13 all sections gain in hardness the moment the heat treatment is commenced. From Figure 4.13, sections I and II achieve maximum hardness within the first 30 minutes of solution treatment while in section III hardness increases rapidly in the fast 30 minutes and continues to increase marginally until maximum hardness is achieved after 3 hours of solution treatment.

The rapid gain in hardness in sections I and II is attributed to smaller grain cells formed in these sections hence faster precipitation of solutes to grain boundaries. Precipitation in section III takes more time as it has larger grain cells and precipitation of solutes to boundaries is slower thus maximum hardness is obtained after a longer periods of solution treatment.

4.8 Ductility

4.8.1 Results

Ductility was expressed in terms of percentage elongation. Figure 4.14 and Table H.3 in Appendix **H** show percentage elongation of sections I, II and III.

From Figure 4.14 percentage elongation in as-cast state was 4.4% in section I, 2.9% in section II and 2.0% in section III. When solution treated was carried out for 30 minutes in section I, percentage elongation increased by 5% and remained about the same level even when solution treatment was carried out for 1 hour, 3 hours and 6 hours.

In section II elongation increased from as-cast state by 3% after 30 minutes, increasing marginally to 3.1% after 1 hour solution treatment, 3.2% after 3 hours and reached a

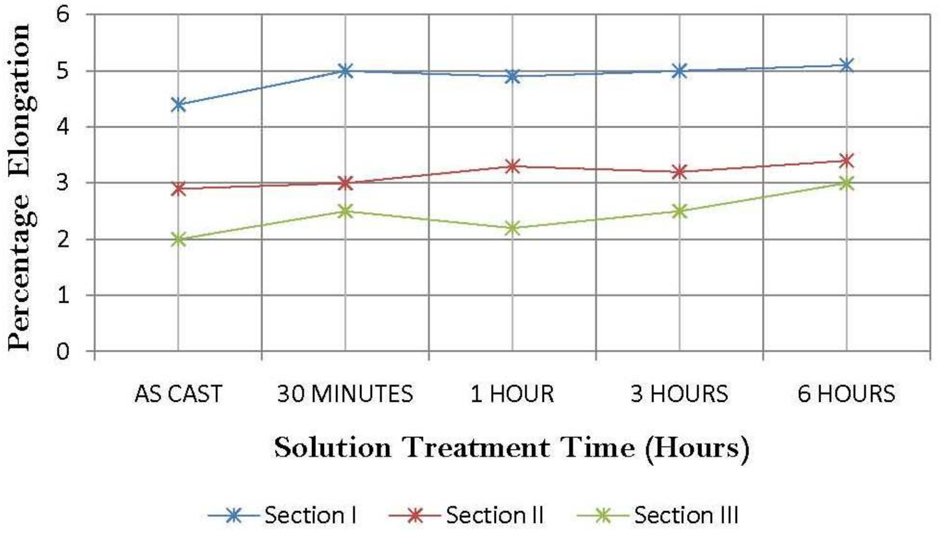


Figure 4.14: Trends in Elongation across Sections I, II and III

maximum of 3.4% after 6 hours.

In Section III there was little increase in elongation with heat treatment, increasing only 1% after 6 hours of solution treatment.

4.8.2 Discussion

From Figure 4.14 it was noted that ductility only gained during initial stages of solution treatment. The effect of cooling was observed from all sections in as-cast state and effect of solution treatment after exposure at various solution times. In section I ductility achieved after 30 minutes was nearly same to that obtained after 6 hours solution treatment. The trend was similar to sections II although maximum ductility was achieved after 1 hour solution treatment respectively.

Gains in ductility in initial stages were attributed to the modified structure and microstructural evolution caused by heat treatment. When the alloy was solution treated there was spheroidisation and coarsening of eutectic silicon particles. The smaller and more spheroidised particles of section I allowed the alloy material to strain more before fracturing and thus better ductility. Particles of section II and III spheroidised slower than those of section I and therefore achieve maximum ductility after longer solutioning. When solution treatment was conducted for longer periods of 1 hour, 3 hours and 6 hours the materials hardness increased and these countered the effect of ductility as observed in Figure 4.14.

4.9 Resistance to Impact

4.9.1 Results

Figure 4.15 (also Table H.4 and Figure H.4 in Appendix **H**) shows trends and results of impact energies obtained from charpy impact tests of sections I, II and III in the as-cast state and as functions of heat treatment. The effect of cooling on impact energy is apparent as the recorded value in as-cast state for sections I (1.62 J) is higher than in section II (1.145 J) and section III (0.935 J). When heat treatment is applied, it is noted that each section responds differently. Section I is sensitive to heat treatment as after 30 minutes impact energy is 21% greater than observed in as-cast state. When solution time is increased to 1 hour, 3 hours and 6 hours impact energy increases by 48%, 56% and 86% respectively. From Figure 4.15 it is observed that there is a gradual increase in section II of 25%, 35%, 64% and 85% after 30 minutes, 1 hour, 3 hours and 6 hours respectively.

The response in section III is poor with increases of 15%, 18%, 23% and 28% after 30 minutes, 1 hour, 3 hours and 6 hours solution treatment respectively.

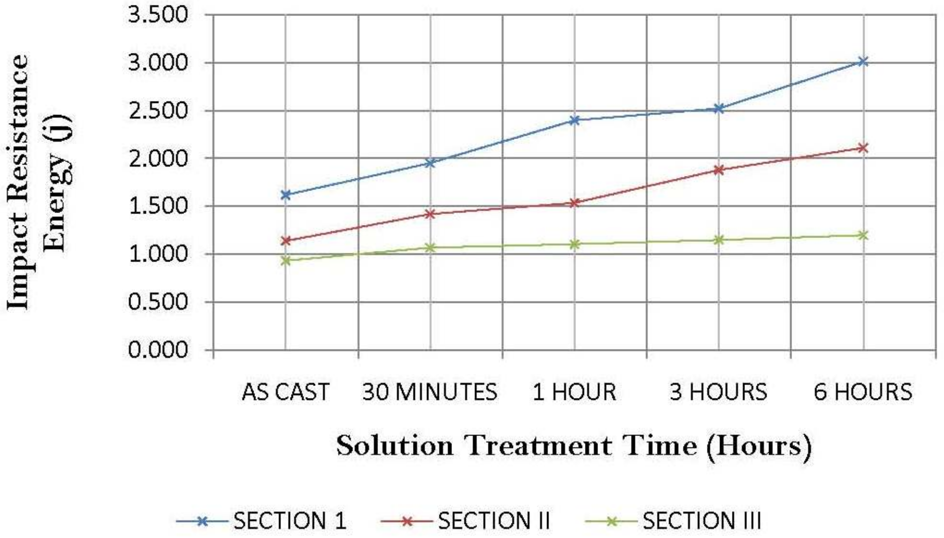


Figure 4.15: Trends in impact energy in Sections I, II and III

4.9.2 Discussion

In as-cast state, section I records higher impact strength than section II, and the latter higher than section III. This is attributed to cooling as sections of faster cooling (section I) register better impact strength values than those of slower cooling rate (section II and III) [12].

When heat treatment is carried out, there are substantial gains in impact strengths that are linked directly to microstructural transformations that accompany the process. After 30 minutes solution treatment there is fragmentation of silicon eutectic and spheroidisation of these particles in all sections [6, 15].

The smaller eutectic particles increase the materials toughness and result in improved resistance to impact loads. With further solution treatment, spheroidisation stops but impact strengths in section I and II increase significantly and gradually. Both sections (I and II) respond in similar manner after same periods of solution treatment but strengths in section I exceed those in section II. The continued gain in impact strength is attributed to the corresponding increase in spheroidisation and particle size spacing [6, 15] that is observed after 1 hour, 3 hour and 6 hours of solution treatment.

In section III however, increase in impact strengths is marginal even when this section is solution treated for longer periods. With continued solution treatment it registers little gain as a result of the poor spheroidisation and formation of a coarse grain structure. The combination of these two occurrences predisposes the alloy to brittle behavior and therefore poor resistance impact loads.

4.10 The Industrial Foundry Survey

4.10.1 Results

4.10.1.1 Foundry Operations

The study was conducted on nineteen foundries; fifteen were based in Nairobi, one in Nakuru and one in Kisumu and one in Thika town. Two companies based in Nairobi had fully fledged operations with large production runs and had been in operation for past 25 years or more. Other foundries in Nairobi operated in Kariobangi light industries area with no formal organization structures and were considered a part of Jua Kali sector.

Foundries in Nakuru town had either abandoned mainstream casting and had either scaled down their operations or diversified to other related metal works like metal fabrication and repair works. They however, made exceptions to cast when a customer demanded a product or would outsource when the needs exceeded their capacities. A foundry in Kisumu cast on a need basis and specialized in making customized parts as opposed to general production for mass consumption.

The foundry in Thika was newest and had fabricated its own equipment to suit requirements in the industry. They had acquired casting equipment such as crucibles, fabricated a tilting furnace and had ventured into production of motor cycle parts with plans to carrying out mass production in future.

Foundries in Kariobangi operated in temporary sheds, employed workers on casual basis and collectively accounted for majority of aluminium castings. These artisans engaged in production of aluminium items for artistic value or for meeting functional needs. Many specialized in particular products casting in batch runs based on demand. Some items produced included crucifixes; meko stove grills, automobile spacers, meat mincers and potato chippers. Others were aluminum pots, pans, hack saw handles, pulleys and window latches. To a smaller scale low demand items such as gears, pulleys, shafts and piston rods were cast. However production was dictated by orders that also determined the output volume.

Figure 4.16 and Table I.1 in Appendix I.1 give a summary of the average number of parts produced annually by the foundries in the study. Figures 4.17, 4.18 and 4.19 show some finished aluminum cast items sold in local and regional markets.

The two largest foundries in Nairobi had a variety of products and were flexible enough to customize for individual customers and cast for mass consumption. Among their range of products were pulleys, impellers, winch box housings, pump housings, gears and shafts. Their products were of better finish with some emphasis on quality compared to those in the jua kali sector.

Foundries in Kisumu and Nakuru had a small range of products and manufacturing was carried out on a need basis. Some of their products were bushes, automobile accessories and blanks for making gears.

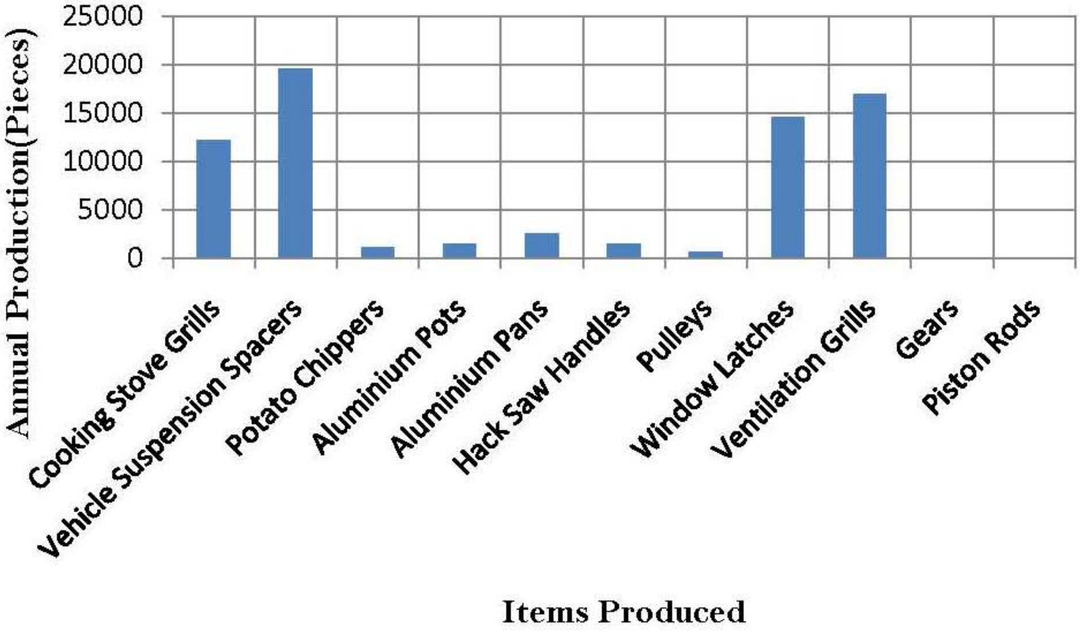


Figure 4.16: Number of select parts cast annually by foundries involved in the survey

Figure 4.17: Castings for decorative purposes (a) used on gates and metal grills (b) used on windows: Courtesy of Willis Mutila, Kariobangi Light Industries.

Of all foundries in the study, two employed workers on permanent terms and the rest on daily wage basis. No formal engagement contracts were made with those numbers recruited on any particular day determined by the bulk of work or urgency of orders.

Figure 4.18: (a)Motor cycle pump casing (b) Water tap: Courtesy of Olietex Foundries, Kariobangi Light Industries.

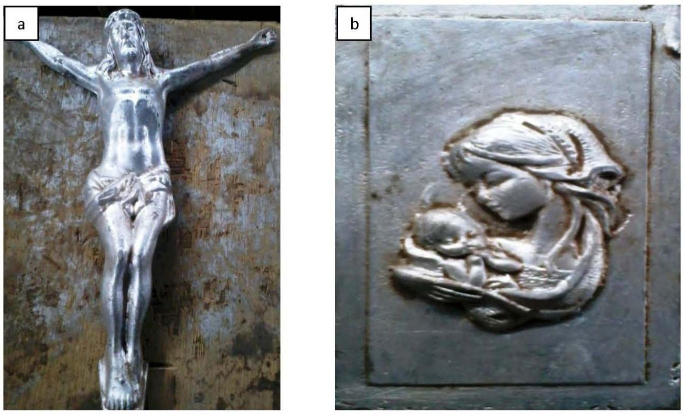


Figure 4.19: Artistic castings (a) Crucifix (b) Religious portraits: Courtesy of Munyi Casting Enterprises, Thika..

Figure 4.20 shows 12 establishments employed between 1 to 10 wagers at a time, with four employing 11 to 20; two foundries 21 to 31 and only three could employ more than 30 employees.

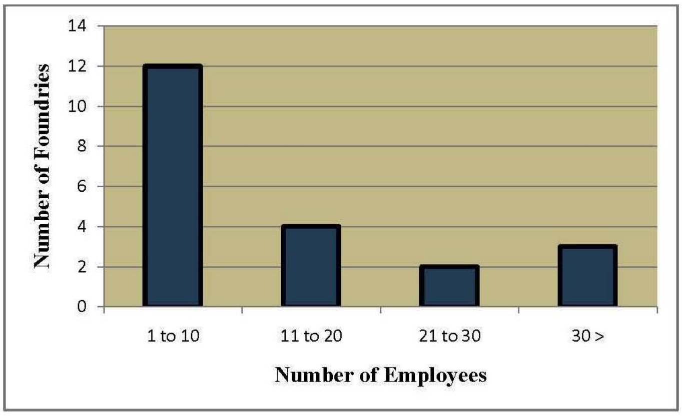


Figure 4.20: Number of foundries and staff employed

4.10.1.2 Quality Control

Quality control is always at the heart of any sustainable production business. In foundry industry quality begins with proper control of inputs, right equipment, type of process used and degree to which process parameters can be controlled.

All foundries in the study used aluminium from scrap as their primary raw material. Scrap selection was done manually and no scientific method was employed; none had a spectrometer or any other equipment with the ability to classify a material according to its elemental composition.

In the two most established foundries in Nairobi, scrap selection was conducted by visual examination where scrap was categorized according to its previous function. For example cylinder heads would be in one heap, pistons, aluminium alloy wheels and other similar pieces would form their own distinct heaps. However when casting began all scrap was mixed without regard of the heap it originated. The need for separation was for convenience purposes such as cleaning and weighing rather than quality control.

At the Jua kali sheds of Kariobangi selection of scrap was based on size of individual pieces of scrap and what was generally referred to as 'hard' or 'soft' aluminium. Hard aluminium referred to ex-automobile parts such as pistons, cylinder heads, sump guards or alloy wheels. Soft aluminium referred to wrought aluminium products such as pots, door paneling or cabinet frames. 'Hard' aluminium was preferred choice for casting but 'soft' aluminium was occasionally added when the melt was too 'hard'.

Quality requirements therefore that a sound product be of an alloy of consistent chemical composition was non-existent. This practice was repeated in all foundries and illustrated a lack of knowledge in the need methodical scrap selection. While this may not have been a problem for the product to be sold locally, it would fail preliminary requirements for export to many international markets. Figure 4.21 shows selected scrap items and preference of users.

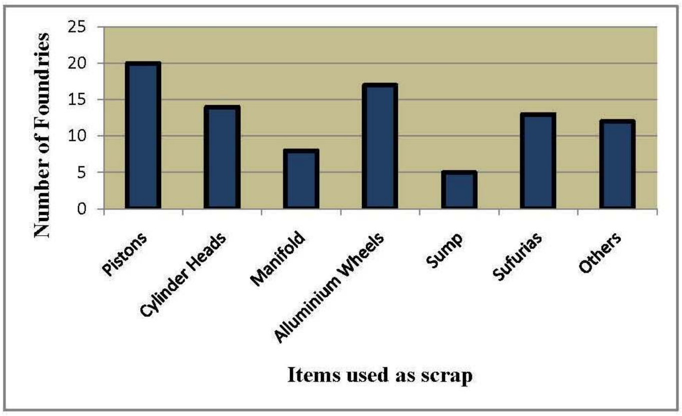


Figure 4.21: Types of common items used for scrap in local foundries

Other essential inputs necessary for achieving quality products are melt additives. Figure 4.22 shows melt treatment agents and number of companies that use them.

Melt treatment is an essential part of casting as a metal is brought as close as possible to its initial manufacture state. Effective melt treatment therefore has a direct influence on quality of a final product. In this study it was found that only three foundries

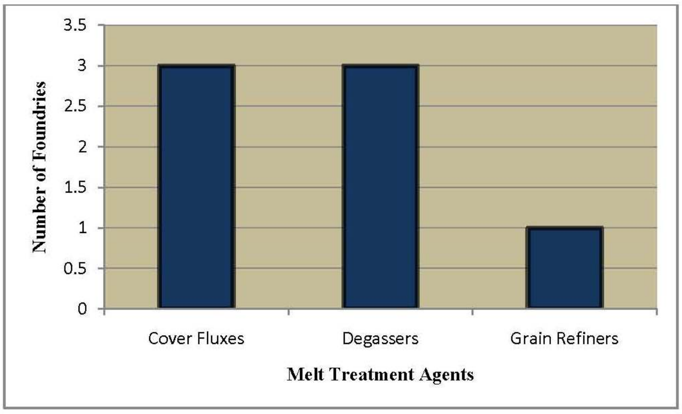


Figure 4.22: Chemical additives used in treating aluminium melt

partially applied the practice of melt treatment. These were the two big established firms in Nairobi and one in Thika town. The only melt treatment procedures however were grain refinement and degassing of the melt. Other essential practices such as microstructure modification, melt filtration or addition of corrector elements such as iron or manganese was deemed expensive and therefore nonexistent. Melt treatment was also not satisfactory as degassers and grain refiners were applied without clear ratios or strict procedures. Treatment by degassers or refiners was left to foundry man to estimate quantities to be added, while precise times for making such additions were determined by experience.

Another factor of consideration in determining the casting quality was the melting process. The process of making a sound casting is sensitive to heating and equipment used. Strict adherence to melting procedure and control of process parameters such as melting, tapping and pouring temperature always yield good quality castings. Equipments are equally important as they regulate temperature and provide a shield to contamination. All foundries under study were found to use petrochemical oils as heating medium. However there were differences in melting equipment as those in the Jua kali sector of Kariobangi used innovative gravity oil spray and heating hearth systems that eliminated the need for a melting crucible. This method inevitably exposed the melt to contamination from soil and allowed gas pickup from atmospheric gases. This method was popular in most informal foundries and it was used in foundries in Nakuru and Kisumu.

Larger foundries in Nairobi and Thika had well structured furnaces that could contain and melt metal in crucibles. Temperature controls were much better and contamination was limited by protective crucible walls.

All these processes achieved the primary objective of melting scrap although determination of melting parameters such as when the melt was ready was conducted without any equipment. There were no thermocouples and which meant that on occasions the metal would overheat and deteriorate its mechanical properties.

After casting it was often essential that secondary process be applied with the aim of adding value to the cast components. These could be used to elevate strength, remove rough edges, bring parts to specification or add to aesthetic appeal.

The study therefore attempted to determine whether any process existed within foundries that addressed these issues. Figure 4.23 shows tallies of selected value addition processes against the number of foundries that applied them. From figure 4.23 it is evident that no organization or establishment practiced heat treatment of parts, anodizing, chemical plating or electroplating. The only secondary processes were machining and spray painting. Ten foundries had simple machines including drills, grinders, lathes and milling machines. They were therefore able to do simple operations such as facing, drilling and grinding. Figure 4.24 shows a cast motor vehicle suspension spacer, finished by drilling and boring provisions for fastenings. Painting was carried out by three foundries that undertook castings for decorative purposes. Aluminium spray paint was used to primarily gloss the casting.

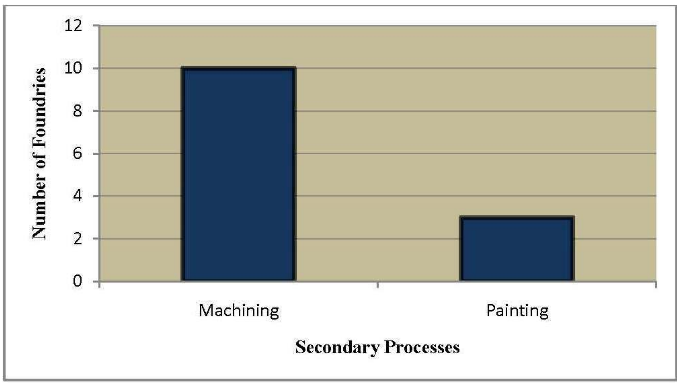


Figure 4.23: Secondary production processes conducted by foundries

Figure 4.24: A motor vehicle spacer cast and finished in a kariobangi foundry

Figure 4.25 shows distribution of education levels of foundry men in the study. It was found that 44% had primary school education, 39% secondary school education, 13% had completed studies in a middle level college or technical training institute and only 3% had attained an undergraduate university and above. The overall study assessment concluded that foundries lacked clear policies of integrating quality in their products. Inputs and processes lacked considerations that controlled consistency of final products. Castings were never tested for mechanical strength or otherwise. The only post casting inspections conducted were visual and this meant that they could not be certified by the Kenya Bureau of Standards (KEBS) for local market or export purposes.

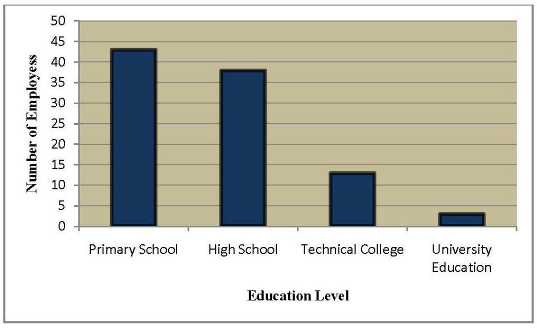


Figure 4.25: Distribution of education levels of foundry men in the study

4.10.2 Discussion

4.10.2.1 Challenges facing the Foundry Industry

As much as foundries provide opportunities for growth and development, they are faced by myriads of challenges. This study attempted to determine issues that undermined the practice.

From the onset it was obvious those in jua kali sheds especially in Kariobangi had problems related to infrastructure. Roads leading to these foundries were dilapidated, poorly planned and difficult to access by vehicles especially when it rained. This meant that raw materials and finished products had to be carried for considerable distances to road sides so as to access vehicles.

The sheds that formed the foundries were made of iron sheets supported by timber or pole frames that could not adequately provide security for goods storage. The effect was that jobs were planned to ensure they ended within the day. Overnight stay would force the owners to sleep over or employ temporary night guards as the castings were susceptible to theft.

The main reasons sheds were constructed in this manner was attributed to a number of factors. Key among them was the fact that they lacked ownership of the parcels of land on which they operated. They therefore could not invest in permanent structures and could not use the plots of land as collateral to get funding from lending institutions.

Another challenge faced by foundries especially in the jua kali sector was the lack of formal training. Staffs were recruited arbitrarily, learnt their craft on the job and developed their skills over time. This coupled with their low basic education levels meant that they lacked technical knowledge on materials, melt treatment and process manipulation techniques relevant for a high level casting.

The other critical effect of lacking in technical knowledge was evidenced in the quality of parts produced. Most foundries lacked basic manufacturing essentials such as repeatability, consistency in production process, consistency in raw material composition and final quality assessment. They could therefore not get quality approvals from bodies such as Kenya Bureau of Standards (Kebs) or any other international quality assurance body.

Of all challenges faced by foundries in this study the greatest was competition from products originating from markets of Asian nations. The general agreement was that the imported products were of good quality and were favored by consumers. The inability to produce similar or better quality goods to compete with these imports was blamed on lack of institutionalized mechanisms of government support to this sector, lack of avenues to gain relevant knowledge and poor manufacturing techniques.

Findings on material development carried in this study of short solution heat treatment of aluminium would therefore add to the field of knowledge and solutions that can be applied by local foundries in improving casting techniques and quality; this would give them confidence in venturing into manufacturing of castings such as winches, water pump housings, motorcycle crank cases, cylinder heads amongst others.

CHAPTER FIVE

5.0 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

In this study it was established that;

- Addition of strontium master alloy to the aluminium A356 alloy sand casting modifies the microstructures from the flat plate shape like structures to the more rounded fine fibrous morphology.
- Castings of faster cooling rate yield high values of YS, UTS, ductility, hardness and resistance to impact in the as-cast state while those having slower cooling rates have comparatively lower values of the same.
- Heat treatment causes fragmentation and spheroidisation of the eutectic silicon phase with increased solution treatment time resulting in further spheroidisation and increase in interparticle spacing. The effects of these microstructural changes are increased YS, UTS, ductility, hardness and resistance to impact.
- The casting industry in the country has low levels of education, skilled manpower, knowledge and information on foundry practices. This therefore means that for short heat treatment techniques to benefit the local industry comprehensive training on best foundry practices have to be developed.

5.2 Recommendations

This research showed that a short cycle treatment can be used to manipulate the mechanical properties of Al-Si alloy with appreciable results and benefits to the casting industry. However the following areas would add value to the work carried out in this study and is recommended for further research

- A Training Needs Assessment (TNA) be conducted to establish a curriculum for training foundry men on modern casting practices need for quality in their products.
- The effect of short cycle treatment on other mechanical properties such as creep and fatigue be investigated as Al-Si alloys find applications in many areas of varying stresses.
- Other aluminium alloys including eutectic and hypoeutectic alloys be investigated to determine their response to short solution heat treatment cycles.

REFERENCES

[1] Askeland R. D., *The Science and Engineering of Materials.* Nelson Thornes Ltd, 3rd ed., 1998.

[2] *www.google.co.ke.* Accessed March, 2012.

[3] ASTM E 092, *Standard Test Method for Vickers Hardness of Metallic Materials.* ASTM, 2003.

[4] ASTM E 112, *Standard Test Methods for Determining Average Grain Size.* ASTM, 1996.

[5] Brown J. R., *Foseco Non-Ferrous Foundryman's Handbook.* Oxford, Butterworth-Henemann, 11th ed., 1999.

[6] Pagonis G. A, *The Light Metals Handbook.* Buttersworth-Heinemann, 1996.

[7] American Society for Metals, *Metals Handbook: Desk Edition.* American Society for Metals, 1990.

[8] Grosselle F., Timelli G., Bonollo F. and Molina R., "Correlation between Microstructure and Mechanical Properties of Al-Si Die-cast Engine Blocks," *Material Transactions,* Vol. 27-2, 2009.

[9] Dingmann D. and Handzel G., "Short-Cycle Solution Heat Treatment in a Modern Fluidized Bed," *Technomics Limited Liability Company*, 2003.

[10] Cavaliere P., Cerri E. and Leo P., "Effect of Heat Treatment on Mechanical Properties and Fracture Behavior of a Thixocast A356 Aluminium Alloy," *Journal of Materials Science,* Vol. 39, pp. 1653–1658, 2004.

[11] Jain R. K. and Gupta S. C, *Production Technology.* Channa Publishers, 1989.

[12] Gruzleski J. E. and Closset B. M, *The Treatment of Liquid Aluminum-Silicon Alloys*. Des Plaines, 1990.

[13] Suryanarayana C. and Rao M. H, "Rapid Quenching Studies of a Commercial Aluminium Alloy 2014," *Journal of Materials Science letters,* Vol. 6, pp. 317–320, 1987.

[14] Mondolfo L. E., *Aluminium Alloys: Structure and Properties.* Butterworth Co. Ltd., 2nd ed., 1976.

[15] Zhang D. L., Zheng L. H. and StJohn D. H., "Effect of Short Solution Treatment Time on Microstructure and Mechanical Properties of Modified Al-7wt.%Si-0.3wt.%Mg Alloy," *Journal of Light Metals,* Vol. 2, pp. 27–36, 2002.

[16] Ogris E., Wahlen A., Luchinger H. and Uggowitzer P. J., "On The Silicon Spheroidisation in Al-Si Alloys," *Journal of Light Metals,* Vol. 2, pp. 263–269, 2002.

[17] Jahromi S. A. J, Dehghan A. and Malekjan S., "Effect of Optimum Amount of Sr and Sb Modifiers on Tensile, Impact and Fatigue Properties of A356 Aluminium Alloys.," *Iranian Journal of Science and Technology,* Vol. 28 no. B2, pp. 474–477, 2004.

[18] Tanski T., Dorbranski L.A. and Maniara R., "Microstructures of Mg-Al-Zn and Al-Si-Zn Cast Alloys," *Journal of Achievements in Materials and Manufacturing Engineering,* Vol. 38, 2010.

[19] Keyser E. C., *Materials Science in Engineering.* CBS Publishers and Distribution, 4th ed., 1998.

[20] Lasa L. and Rodriguez-Ibabe J. M., “Evaluation of the Main Intermetallic Phases in Al-Si-Cu-Mg Casting Alloys during Solution Treatmentt,” *Journal of Materials Science,* Vol. 39, pp. 1343–1355, 2004.

[21] Ceschini L., Alessandro M., Morri A., Gamberini A., Messieri S., “Correlation between Ultimate Tensile Strength and Solidification Microstructure for the Sand Cast A357 Aluminium Alloy,” *Materials and design,* Vol.30, pp. 4525–4531, 2009.

[22] George Vander Voort, “Using Microstrucrural Analysis to Solve Practical Problems,” *TECH NOTES,* Vol. 1, 1997.

[23] Sathyapal h., Narayan P. K., “Modification of Eutectic Silicon in Al-Si alloys,” *Journal of Material Science,* Vol. 43, pp. 3009–3027, 2008.

[24] Michael T. Stawovy, Alex O. Aning, Chair William Curtin, Stephen L. Kampe, William T. Reynolds, John A. Wert, “Processing of Aluminum Alloys Containing Displacement Reaction Products,” *Journal of Material Science,* Vol. 43, p. 14, 2000.

[25] Shabestari S. G.,and Shahri F., “Influence of Modification, Solidification Conditions and Heat Treatment on the Microstructure and Mechanical Properties of A356 Aluminium Alloy,” *Journal of Materials Science,* Vol. 39, pp. 2023–2032, 2004.

[26] ASTM B 917M-01, *Standard Practice for Heat Treatment of Aluminium-Alloy Castings from all Processes.* ASTM, 2001.

[27] ASTM B557-02a, *Standard Test Methods of Tension Testing Wrought and Cast Aluminum and Magnesium Alloy Products.* ASTM, 2002.

[28] Jorstad J. L., Pan Q. Y. and Apelian D., "Solidification Microstructure affecting Ductility in Semi-Solid-Cast Products," *Metal Science and Engineering,* Vol. 413, pp. 186–191, 2005.

[29] Sheng-Long L., Yen-Hung T., Shan-Noon Y. and Jing-Chie L., "Effect of Pre-Aging on Precipitation Hardening in Al-Si-Mg Alloys," *Scandinavian Journal of Metallurgy,* Vol. 27, pp. 112–115, 1998.

[30] Jian X., Meek T. T. and Han Q., "Refinement of Eutectic Silicon Phase of Aluminium A356 Alloy using High-Intensity Ultrasonic Vibration," *Scripta Materialia,* Vol. 54, pp. 893–896, 2006.

[31] Ogris E, Wahlen A., Luchinger H. and Uggowitzer P.J, "Silicon Spheroidisation Treatment of Thixoformed Al-Si-Mg Alloys," *Material Science,* Vol. 2, pp. 149–154, 2002.

[32] ASTM B 26/B 26M, *Standard Specification for Aluminium-Alloy Sand Castings.* ASTM, 2003.

[33] Nogita K. and Dahle A. K, "Determination of Eutectic Solidification Mode in Sr-Modified Hypoeutectic Al-Si Alloys by EBSD," *Material Transactions,* Vol. 42, pp. 207 – 214, 2(2001).

[34] Qian M., Yi F., Zhang D., Pan X., Brody H. D. and Moral J. E., "Solute Distribution and Phase Appearance in As-Cast Al-Si-Cu-Mg-Fe Alloys," *Institute of Material Science,* Vol. 42, 2009.

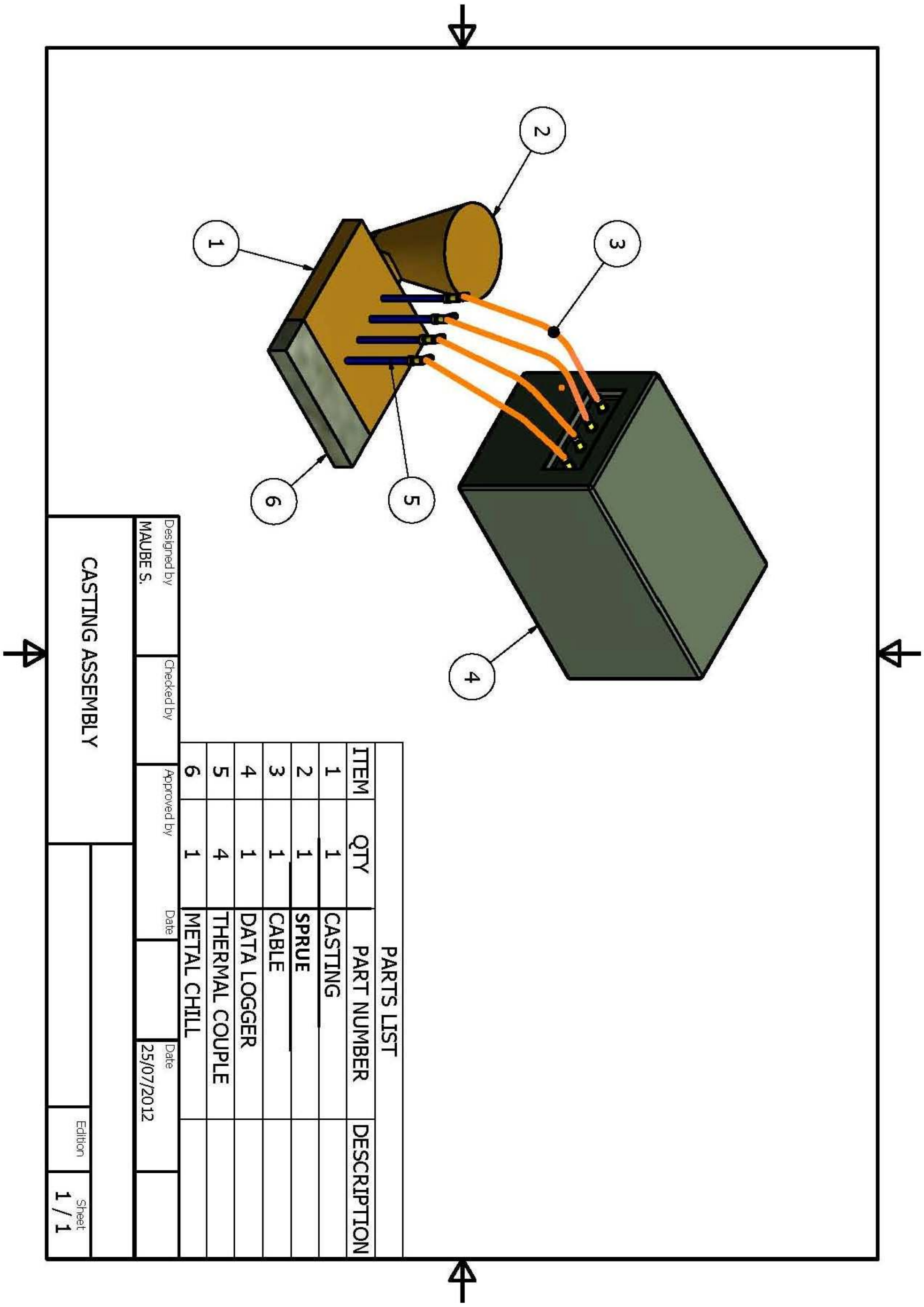
[35] Sujoy K. C. and Diran A., "Optimization of Heat Treatment Using Fluidized Bed (FB) Reactors," *Metal Processing Institute,* Vol. 39, pp. 1653–1658, 2003.

[36] ASTM B0023, *Test Methods for Notched Bar Impact Testing of Metallic Materials.* ASTM, 2002.

[37] ASTM 0003-01, *Guide for Preparation of Metallographic Specimen.* ASTM, 2001.

APPENDIX A

A.1 Casting Assembly



PARTS LIST

ITEM	QTY	PART NUMBER	DESCRIPTION
1	1	CASTING	
2	1	**SPRUE**	
3	1	CABLE	
4	1	DATA LOGGER	
5	4	THERMAL COUPLE	
6	1	METAL CHILL	

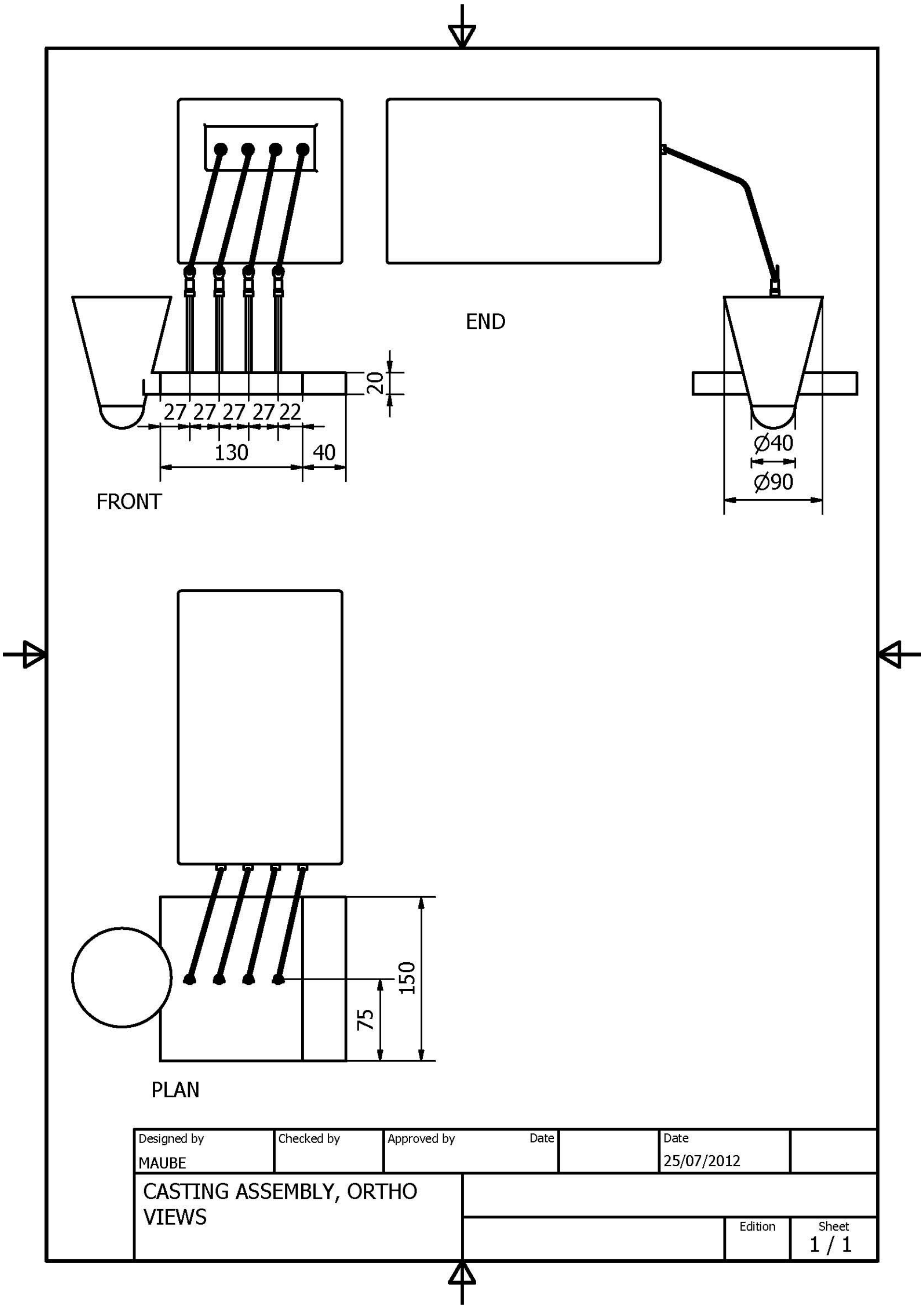
Designed by	Checked by	Approved by	Date	Date
MAUBE S.				25/07/2012

CASTING ASSEMBLY

Edition	Sheet
	1 / 1

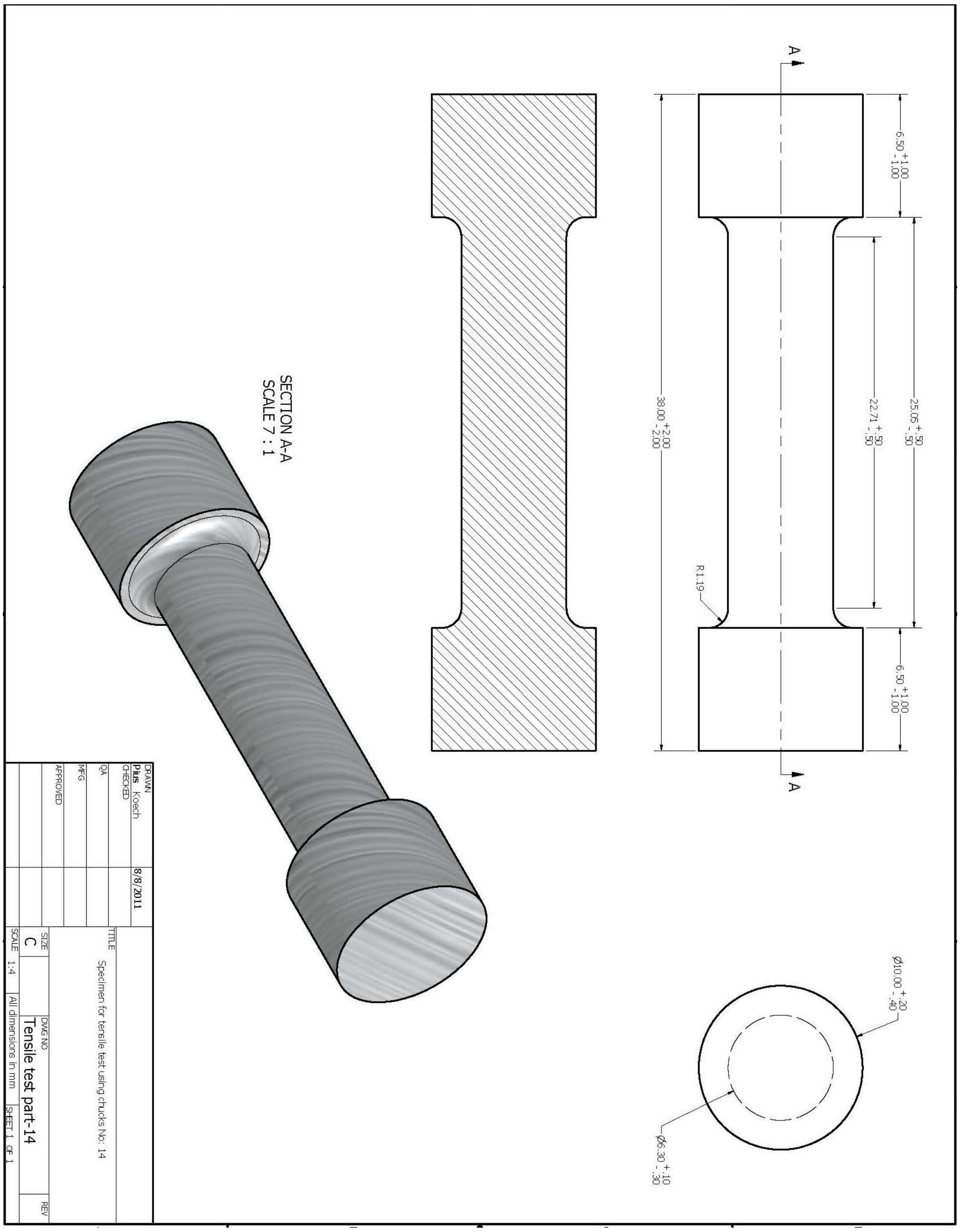
APPENDIX B

B.1 Casting Assembly Orthographic View



APPENDIX C

C.1 Tensile Test Specimen



APPENDIX D

D.1 Questionnaire Guide

Please note that the information provided will be treated in confidence and there is no obligation to include the name of the organization in the Section D.1.1 below. Thank you for completing this survey.

D.1.1 SECTION I

1. Date of visit: ...../....../2011.
2. Name of the Company/business/individual..
   ....
   ....
3. Address ....
   ....
4. Physical Location ....
5. Number of employees ....

D.1.2 SECTION II

1. Type of business establishment
   - Large manufacturing [ ]
   - Foundry shop [ ]
   - Jua kali shed [ ]

- Other [ ] specify ....

2. Does your organization carry out any casting operation? YES [ ] NO [ ]. If yes, what type of materials do you use for the casting operation
   - Ferrous materials [ ]
   - Non-ferrous materials [ ]
   - Both [ ]. Give details..
     ....

3. What kind of products does your organization cast(Specify monthly output)?

Pulley wheels [......]	Gears [......]
Stove grills [......]	Automobile spacers and parts [......]
Pump accessories [......]	Impellers [......]
Handles and household fittings [......]	
Others [......] specify	

4. Does your organization/business/company use scrap metal? YES [ ] NO [ ]. If yes, what are the sources of the scrap used
   - Car dealers [ ]
   - Scrap vendors [ ]
   - Machine shops [ ]
   - Others [ ] specify ....
     ....
     ....

5. What components do you most encounter in the scrap you use?

Pistons [ ]	Manifolds [ ]
Cylinder heads [ ]	Aluminium alloy wheels [ ]
Oil sumps [ ]	Electrical components [ ]
Others [ ] specify	

6. What quality control measures do you apply on selecting scrap metal?

   - Manually selection [ ]
   - Magnetic isolation of ferrous material [ ]
   - Spectrometric isolation [ ]
   - Others [ ] ....

     ....

     ....

7. Do you carry out any pretreatment or cleaning on scrap? YES [ ] NO [ ]. If yes please specify

   ....

   ....

   ....

8. Which of the following casting methods does your organization employ?

   - Sand casting [ ]
   - Die casting [ ]
   - Investment casting [ ]

- Others [ ]

  ....

  ....

  ....

  ....

9. What equipment do you use to facilitate the melting of the aluminium alloy

   - Oil fired crucible [ ]
   - Induction crucible [ ]
   - Charcoal fired crucible [ ]
   - Coke fired [ ]
   - Others [ ]. Give details

     ....

     ....

     ....

     ....

10. Does your organization have a procedure for melting and treating alloys in order to achieve high quality products? YES [ ] NO [ ]. Please state and explain

    ....

    ....

    ....

    ....

11. Are there any eutectic modifiers or additives such as sodium, antimony or strontium that are used to enhance the quality of the finished products? YES [ ] NO [ ]. If yes, describe the modifier used

    - Sodium based modifier [ ]
    - Antimony based modifier [ ]
    - Strontium based modifier [ ]
    - Others [ ] specify

      ....

      ....

      ....

      ....

12. Are there any heat treatment processes employed to enhance the mechanical properties of your products? YES [ ] NO [ ]. Explain further

    ....

    ....

    ....

    ....

13. Does your firm have a procedure for grain refinement? YES [ ] NO [ ]. If yes, state the purpose

    - Improve fluidity [ ]
    - Improve mechanical property [ ]

- other [ ]. Specify

  ....

  ....

  ....

  ....

14. What quality control tests do you carry out on the final products to ensure that the castings are of good quality

Tensile tests [ ]	Impact tests [ ]
Micro analysis [ ]	Macro analysis [ ]
Porosity tests [ ]	Spectrometric analysis [ ]
Others [ ] specify	

15. What kind of problems do you encounter with your products

- Porosity [ ]
- Blow holes [ ]
- Deformation [ ]
- Breakages [ ] Others [ ]. Specify

  ....

  ....

  ....

  ....

16. List some of the equipment you have to facilitate performance of tests

Hardness testing machines [ ]	Charpy/Izod Impact tests [ ]
Tensile testing machines[ ]	X-ray machines [ ]]
Optical microscope [ ]	Spectrometers [ ]
Others [ ] state	

17. In the organizations product segment who are the organizations main competitors

- Large manufacturing firms[ ]
- Local producers [ ]
- Imports [ ]
- Others [ ]. Please specify

  ....

  ....

  ....

  ....

18. What advantages do the competitors posses?

- Better technologies and techniques [ ]
- Better products [ ]
- Cheaper products [ ]

- Other reasons [ ] ....
  ....
  ....
  ....

19. Which areas of use do your products find application

    - Domestic applications [ ]
    - Industrial applications [ ]
    - Others specify [ ] ....
      ....
      ....
      ....

20. What are the main challenges you face as an organization that are related to casting? ....

    ....

    ....

    ....

21. What are the education levels of the staff members in the foundry shop?

EDUCATION	NUMBER OF EMPLOYEES
Primary School	
Secondary School	
Middle Level College	
University Degree and Above	

APPENDIX E

E.1 Cooling temperatures of sections I, II and III in the cast

Table E.1:

Time(s)	**Section I**	**Section II**	**Section III**
5	698.1°C	680.3°C	691.0°C
10	640.6°C	671.8°C	678.8°C
20	625.3°C	626.6°C	627.7°C
30	609.1°C	615.4°C	618.9°C
40	592.8°C	597.7°C	604.1°C
50	562.1°C	598.1°C	596.4°C
60	529.1°C	588.3°C	591.9°C
70	504.9°C	577.5°C	588.1°C
75	488.9°C	563.9°C	578.9°C
80	456.6°C	519.0°C	566.5°C
85	415.2°C	508.8°C	532.6°C
90	405.6°C	476.3°C	519.9°C
100	389.9°C	442.0°C	500.5°C
200	280.2°C	378.3°C	456.7°C
300	199.2°C	308.4°C	380.8°C
400	186.6°C	246.1°C	338.2°C
500	180.6°C	214.0°C	290.1°C
600	176.4°C	208.8°C	270.5°C
700	169.9°C	192.6°C	260.8°C
800	168.0°C	188.8°C	255.8°C

APPENDIX F

F.1 Results of SDAS

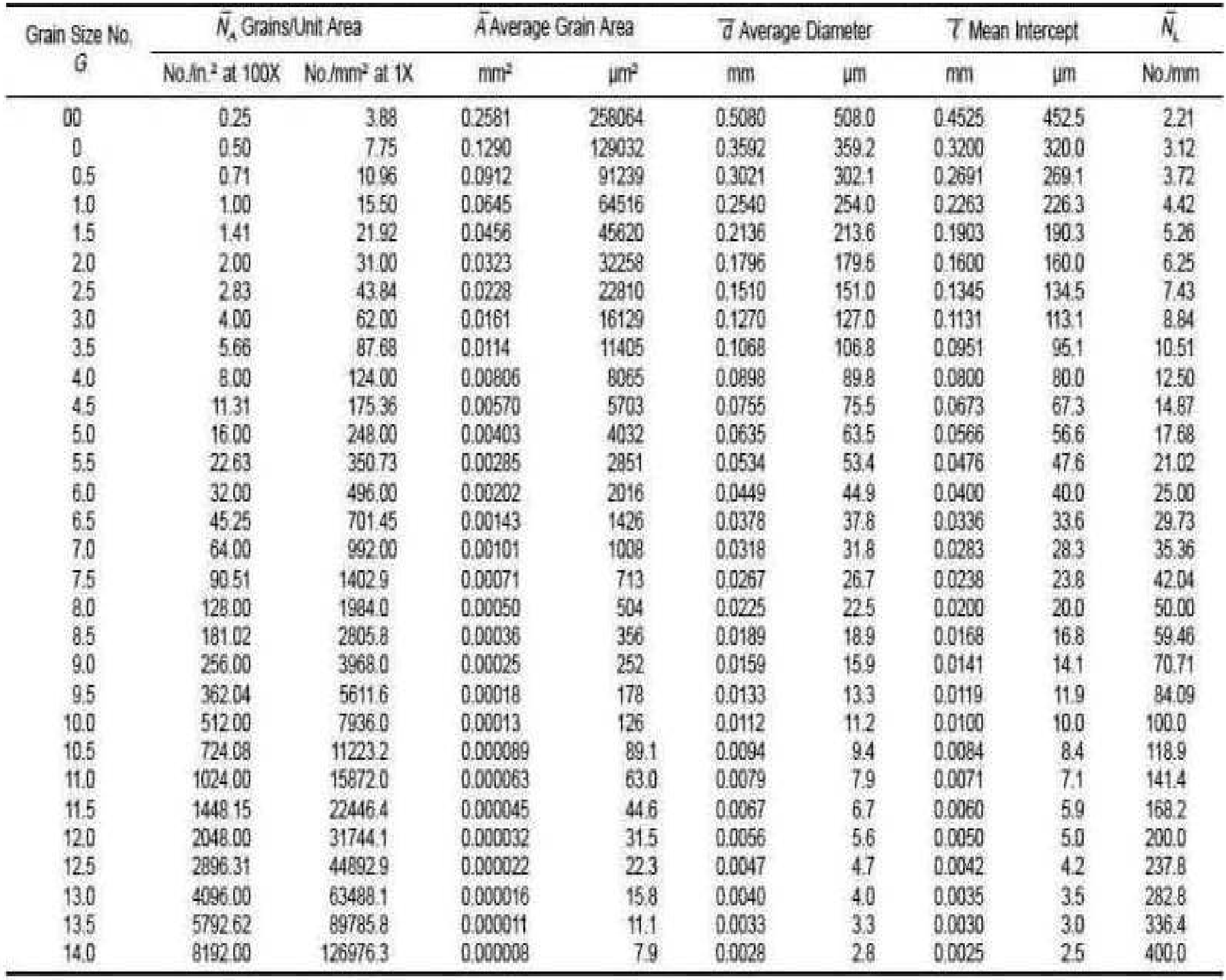
Table F.1: Average SDAS of the sections I, II and III

Section	**SDAS Readings(μm)**				
	First	Second	Third	Fourth	Average
I	33 - 10 - 11	28 - 30 - 30	33 - 31 - 33	32 - 29 - 30	31
II	40 - 35 - 35	33 - 40 - 39	34 - 36 - 37	39 - 38 - 38	37
III	42 - 37 - 41	38 - 38 - 41	43 - 42 - 39	40 - 38 - 42	40

APPENDIX G

G.1 Conversion Table

Figure G.1: Grain Size Relations Computed for Uniform, Random Oriented, Equiaxed Grains [4]



Grain Size No. G	$\bar{N}_A$ Grains/Unit Area		$\bar{A}$ Average Grain Area		$\bar{d}$ Average Diameter		$\bar{\ell}$ Mean Intercept		$\bar{N}_L$
	No./in.^{2} at 100X	No./mm^2 at 1X	mm^2	µm^2	mm	µm	mm	µm	No./mm
00	0.25	3.88	0.2581	258064	0.5080	508.0	0.4525	452.5	2.21
0	0.50	7.75	0.1290	129032	0.3592	359.2	0.3200	320.0	3.12
0.5	0.71	10.96	0.0912	91239	0.3021	302.1	0.2691	269.1	3.72
1.0	1.00	15.50	0.0645	64516	0.2540	254.0	0.2263	226.3	4.42
1.5	1.41	21.92	0.0456	45620	0.2136	213.6	0.1903	190.3	5.26
2.0	2.00	31.00	0.0323	32258	0.1796	179.6	0.1600	160.0	6.25
2.5	2.83	43.84	0.0228	22810	0.1510	151.0	0.1345	134.5	7.43
3.0	4.00	62.00	0.0161	16129	0.1270	127.0	0.1131	113.1	8.84
3.5	5.66	87.68	0.0114	11405	0.1068	106.8	0.0951	95.1	10.51
4.0	8.00	124.00	0.00806	8065	0.0898	89.8	0.0800	80.0	12.50
4.5	11.31	175.36	0.00570	5703	0.0755	75.5	0.0673	67.3	14.87
5.0	16.00	248.00	0.00403	4032	0.0635	63.5	0.0566	56.6	17.68
5.5	22.63	350.73	0.00285	2851	0.0534	53.4	0.0476	47.6	21.02
6.0	32.00	496.00	0.00202	2016	0.0449	44.9	0.0400	40.0	25.00
6.5	45.25	701.45	0.00143	1426	0.0378	37.8	0.0336	33.6	29.73
7.0	64.00	992.00	0.00101	1008	0.0318	31.8	0.0283	28.3	35.36
7.5	90.51	1402.9	0.00071	713	0.0267	26.7	0.0238	23.8	42.04
8.0	128.00	1984.0	0.00050	504	0.0225	22.5	0.0200	20.0	50.00
8.5	181.02	2805.8	0.00036	356	0.0189	18.9	0.0168	16.8	59.46
9.0	256.00	3968.0	0.00025	252	0.0159	15.9	0.0141	14.1	70.71
9.5	362.04	5611.6	0.00018	178	0.0133	13.3	0.0119	11.9	84.09
10.0	512.00	7936.0	0.00013	126	0.0112	11.2	0.0100	10.0	100.0
10.5	724.08	11223.2	0.000089	89.1	0.0094	9.4	0.0084	8.4	118.9
11.0	1024.00	15872.0	0.000063	63.0	0.0079	7.9	0.0071	7.1	141.4
11.5	1448.15	22446.4	0.000045	44.6	0.0067	6.7	0.0060	5.9	168.2
12.0	2048.00	31744.1	0.000032	31.5	0.0056	5.6	0.0050	5.0	200.0
12.5	2896.31	44892.9	0.000022	22.3	0.0047	4.7	0.0042	4.2	237.8
13.0	4096.00	63488.1	0.000016	15.8	0.0040	4.0	0.0035	3.5	282.8
13.5	5792.62	89785.8	0.000011	11.1	0.0033	3.3	0.0030	3.0	336.4
14.0	8192.00	126976.3	0.000008	7.9	0.0028	2.8	0.0025	2.5	400.0

APPENDIX H

H.1 Results of Mechanical tests

Table H.1: Average Yield Stress and Ultimate Tensile Strength values of sections I, II and III.

	Section I		**Section II**		**Section III**	
	YS (MPa)	**UTS** (MPa)	**YS** (MPa)	**UTS** (MPa)	**YS** (MPa)	**UTS** (MPa)
As-cast	118	168	105	147	101	130
30 Minutes	220	236	197	211	163	183
1 Hour	221	253	202	215	190	200
3 Hours	234	264	27	225	195	213
6 Hours	239	270	210	227	208	220

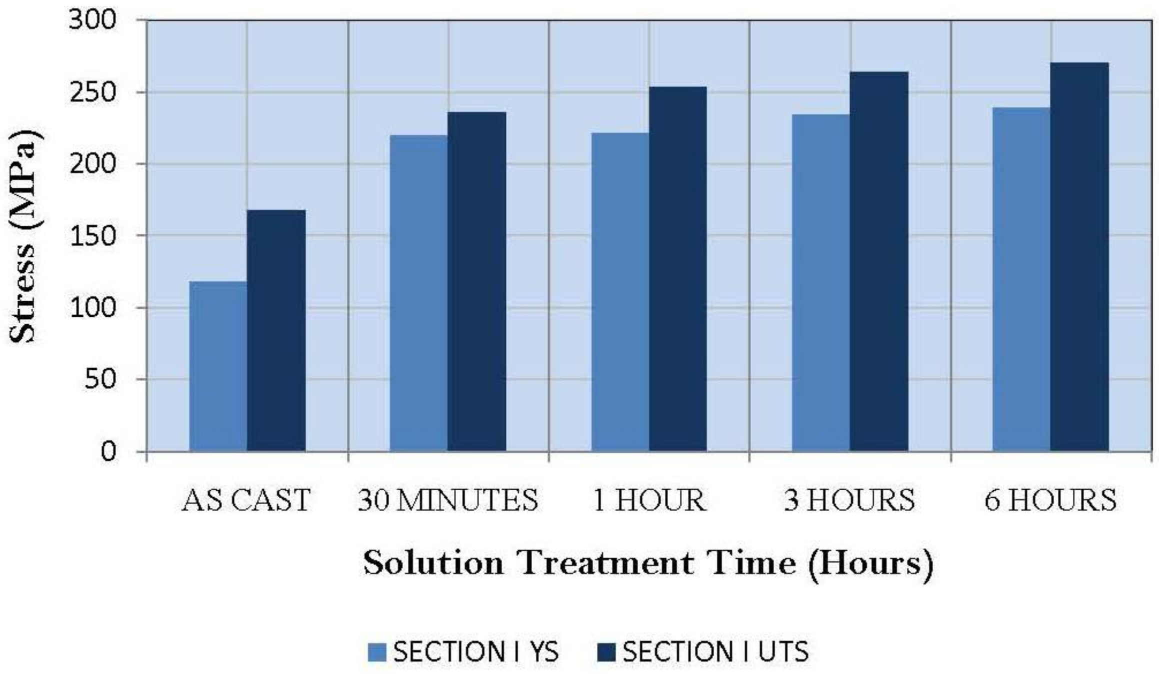


Figure H.1: The YS and UTS values of the Sections I.

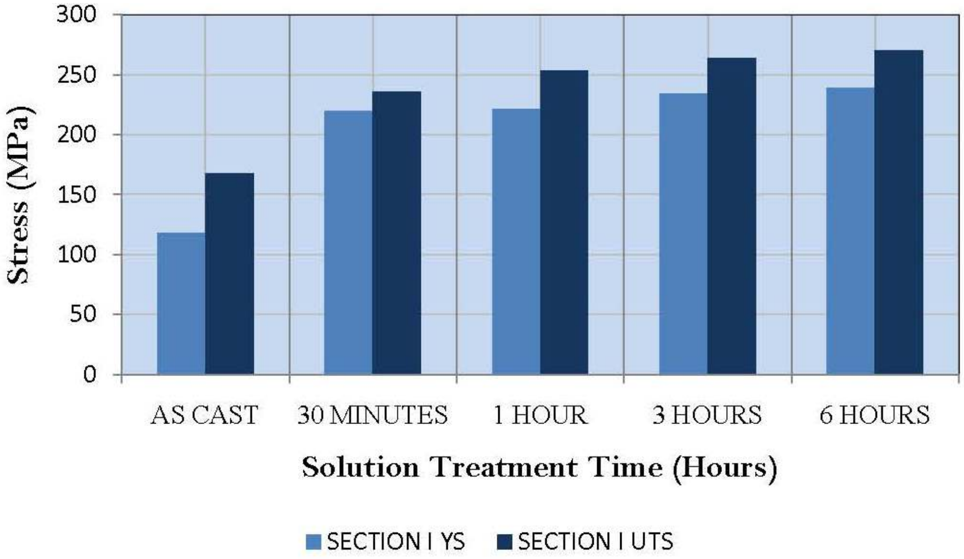


Figure H.2: The YS and UTS values of the Sections II.

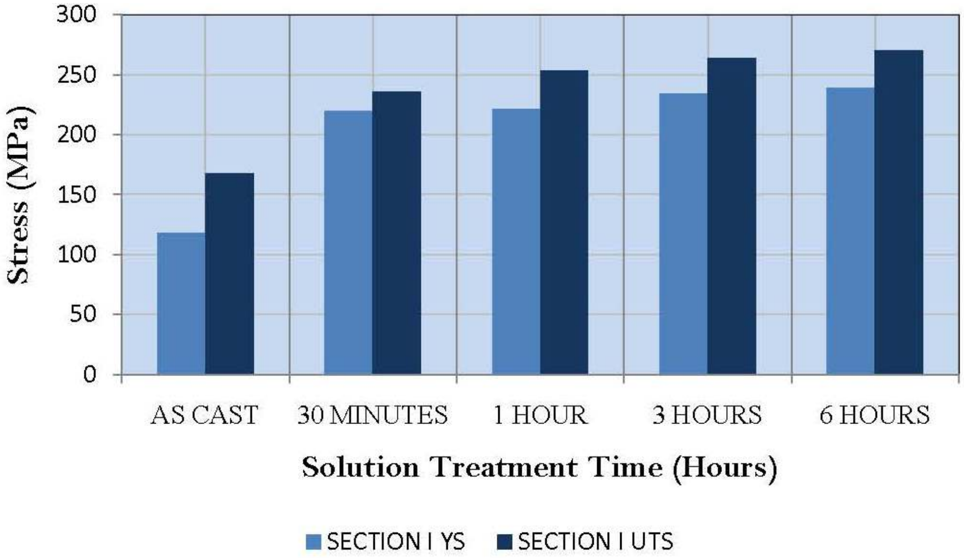


Figure H.3: The YS and UTS values of the Sections III.

Table H.2: Average vickers hardness values obtained for sections I, II and III

Section	**Vickers Hardness**				
	As cast	30 minutes	1 hour	3 hours	6 hours
I	60	69	68	68	62
II	54	63	58	58	61
III	58	66	66	67	67

Table H.3: Average % elongation to Fracture for sections I, II and III.

Section	**% Elongation**				
	As cast	30 minutes	1 hour	3 hours	6 hours
I	4.4	5.0	4.9	5.0	5.1
II	2.9	3.0	3.3	3.2	3.4
III	2.0	2.5	2.2	2.5	3.0

Table H.4: Average Resistance to Impact Energies for sections I, II and III.

Section	**% Impact Energy(J)**				
	As cast	30 minutes	1 hour	3 hours	6 hours
I	1.620	1.952	2.398	2.521	3.012
II	1.140	1.421	1.538	1.880	2.111
III	0.935	1.071	1.107	1.150	1.2008

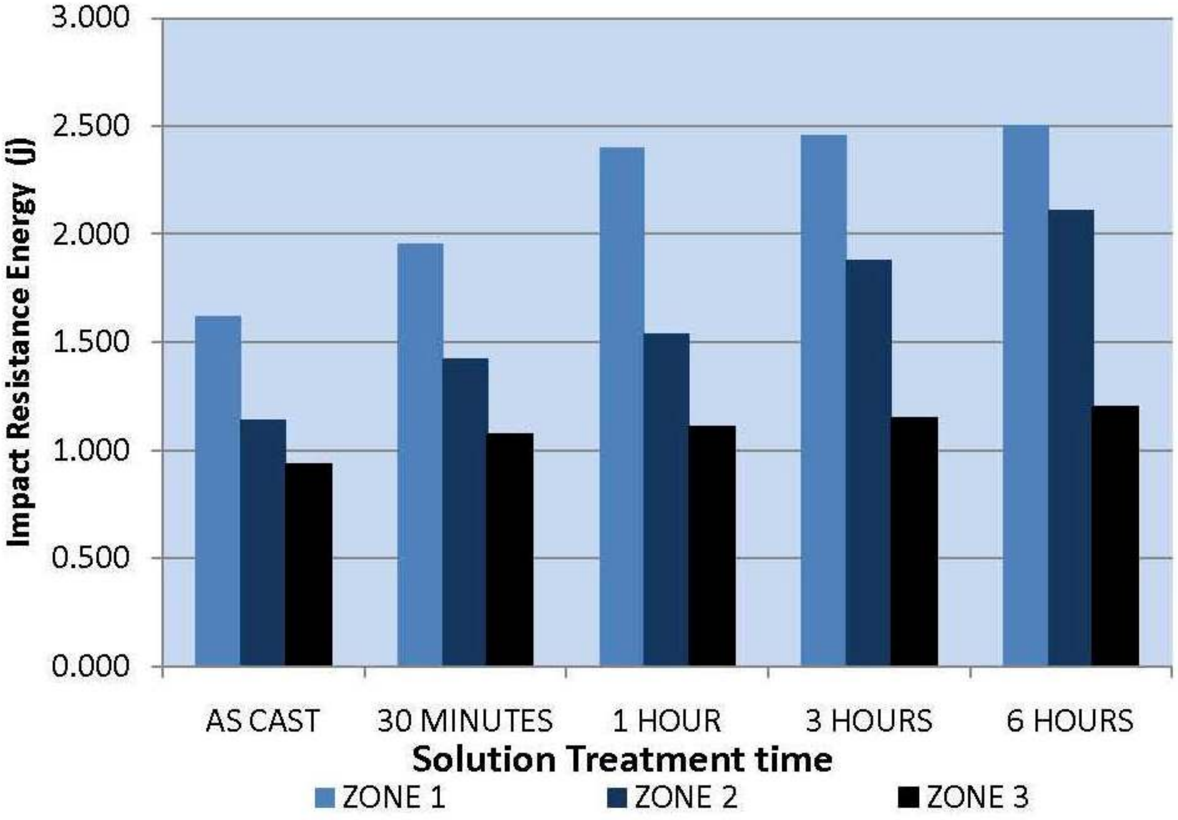


Figure H.4: Trends of impact energy in Sections I, II and III.

APPENDIX I

Number of select parts cast annually by foundries involved in the survey.

Table I.1: Number of select parts cast annually by foundries involved in the survey.

Item	**Annual Production**
Cooking Stove Grills	12250 Pieces
Motor Vehicle Suspension Spacers	19600 Pieces
Potato Chippers	1200 Pieces
Aluminium Pots	1560 Pieces
Aluminium Pans	2600 Pieces
Hack Saw Frames	1500 Pieces
Pulleys	650 Pieces
Window Latches	14600 Pieces
Ventilation Grills	17000 Pieces
Gears	50 Pieces
Single cylinder Piston Rods	20 Pieces