PERFORMANCE EVALUATION OF DIFFERENT MATERIALS AS CHILLS IN SAND CASTING OF ALUMINIUM ALLOY

BY

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M.Sc/ENG/ 08222/2010-2011

A DISSERTATION SUBMITTED TO THE SCHOOL OF POSTGRADUATE STUDIES, AHMADU BELLO UNIVERSITY ZARIA, KADUNA STATE, NIGERIA

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE AWARD OF A

MASTER DEGREE IN MECHANICAL ENGINEERING

DEPARTMENT OF MECHANICAL ENGINEERING,

FACULTY OF ENGINEERING

AHMADU BELLO UNIVERSITY,

ZARIA, NIGERIA.

FEBRUARY, 2016

DECLARATION

I declare that the work in this Dissertation entitled Performance Evaluation of Different Metallic Materials as Chills in Sand Casting of Aluminium Alloy has been carried out by me in the Department of Mechanical Engineering, Ahmadu Bello University, Zaria. The information derived from the literature has been duly acknowledged in the text and a list of references provided. No part of this thesis was previously presented for another degree or diploma at this or any other institution.

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CERTIFICATION

This dessertation entitled Performance Evaluation of Different Materials as Chills in Sand Casting of Aluminium Alloy by Kabiru Muftau RAJI meets the regulations governing the award of the degree of Master in Mechanical Engineering of the Ahmadu Bello University, and is approved for its contribution to knowledge and literacy presentation.

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DEDICATION

This dissertation is dedicated to the Almighty GOD, the Most Beneficent and the Most Merciful.

ACKNOWLEDGEMENTS

Gratitude goes to the Almighty Allah, who had made the completion of this dissertation a reality.

I would like to thank my supervisors, Dr. D. S. Yawas and Prof. A. I. Obi for their contribution to the completion of this work. I acknowledge the lecturers of the Department of Mechanical Engineering who might have in one way or the other contributed to the success of this thesis. My appreciation goes to the Technologists/Technicians in the Department of Mechanical Engineering and Metallurgical and Materials Engineering Department of Ahmadu Bello University, Zaria for the assistance rendered in the practical aspect of the work.

My appreciation also goes to my parents, my wife and friends for their financial support and advice which helped me a lot to make this work a reality, may God reward them all.

ABSTRACT

This study has evaluated the effectiveness of metallic materials as chill in sand casting of aluminium alloy. Four plates of dimension 165mm x 80mm x10mm were cast using sand mould. Steel, copper and brass chills in form of cylindrical bar of geometry 7mm in diameter and 50mm long were inserted, side by side at regular intervals of 30mm in each sand mould and the last sample was left unchilled. Experimentation involved testing of mechanical properties and metallographic analysis of cast samples. The results obtained revealed that the sample chilled with copper has the highest mechanical properties (ultimate tensile strength of 126.13MPa, hardness of 6.8Hv and impact strength of 23.5J).Also sample chilled with copper revealed evenly distributed microstructure which is due to the fast solidification rate of the casting due to the high thermal conductivity of copper. The brass chill sample displayed better mechanical properties (ultimate tensile strength of 115.8MPa, hardness of 5.7Hv and impact strength of 22.4J) than sample chilled with steel (ultimate tensile strength of 101.33MPa and hardness of 5.4Hv). However, the unchilled sample showed the lowest ultimate tensile strength of 70.67MPa, hardness of 4.2Hv and impact strength of 22.5J.

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CHAPTER ONE

1.0 INTRODUCTION

1.1 Background to the study

Metal casting is a shape forming process whereby molten metal is poured into a prepared mould and allowed to solidify such that the shape of the solidified object is determined by the shape of the mould cavity. Sand casting is a metal casting process characterized by using sand as the mould material (Ibhadode, 2001). Casting can be broadly divided into two main categories as expendable and nonexpendable mould casting. It can also be classified according to the mould material used to cast the metal such as sand casting, ceramic casting or metal mould casting and depending on the pouring methods as gravity casting, low pressure die casting and high pressure die casting (Navaneeth, 2009).

Good mechanical properties are achieved in sand casting with the help of metallic insert in the mould known as chill (Mehr, 2012). Strong directional solidification is difficult to obtain in casting of intricate part made of aluminum alloys without the use of chills. The tendency for solidification to start throughout the metal makes proper feeding difficult. Chills must often be used to obtain satisfactory directional solidification (Chi-Yuan *et al.,* 2006).

Chills are metallic inserts moulded into the sand surface to promote high solidification rate in metal casting. Normally the metal in the mould cools at a certain rate relative to thickness of the casting. When the geometry of the moulding cavity prevents directional solidification from occurring naturally, a chill can be strategically placed to help promote it to obtain good mechanical properties. Chills are of two types, internal and external chills.

Chills are usually made from iron, aluminium or copper and can be machined or cast. The type of chill used depends on ease of manufacture and the desired thermal effects of the chill.

Its effectiveness depends on size, conductivity, thermal capacity and the thermal transfer across the molten metal alloy/chill interface. Chilling has been found to improve the soundness of a casting when measured by standard non-destructive testing techniques like radiography or dye penetration inspection, but the influence of microstructure and mechanical properties can be significant (David, 2011).

1.2 Statement of the Research Problem

Normal solidification results a time to poor mechanical properties (hardness, tensile and impact strengths) due to the coarse grains structure after the casting has been produced from the sand mould. The undesired microstructure (coarse grains size and porosity) which leads to poor mechanical properties is due to low rate of solidification (Aran, 2007 and Navaneeth, 2009). The challenge here is to enhance the higher rate of heat removal (solidification).

The need to investigate into some materials that can be used as chillers to assist in fast heat removal from the mould to increase solidification rate becomes very important.

1.3 The Present Research

This research is on the performance evaluation of different material as chill in sand casting to increase solidification rate and to improve the mechanical and microstructural properties.

1.4 Aim and Objectives

The aim of this study is to investigate the effects of different metallic materials as chills in sand casting of aluminium alloy. The specific objectives are:

i. to evaluate the effectiveness of different metallic materials such as copper, mild steel brass as chill in sand casting of aluminium alloys
ii. to evaluate the mechanical properties and microstructure of the chill cast aluminium alloys
iii. to correlate microstructure to mechanical properties of the cast alloys

1.5 Justification

Machine components are usually of complex shape due to the nature of environment the part intended to perform its function. Casting of complicated shape is an integral part of engineering work carried out by foundry man. It is well known that aluminium alloys that freeze over a wide range of temperature are difficult to feed during solidification. The dispersed porosity caused by pasty mode of solidification can be effectively reduced by the use of chills. Most previous works have centered on the uses of metallic mode (direct-chill casting) to enhance solidification. Others have investigated on the placement of chill materials at one side from pouring base to enhance directional solidification. No work has been reported on placement of chill materials at regular intervals to increase solidification of aluminium alloys.

This work will investigates the effectiveness of different metallic chills on the soundness of aluminium alloy in sand casting by placement of the chills at regular intervals so as to enhance directional solidification.

1.6 Scope of the Work

The scope of this work covers;

i. Design of the sand mould by inserting the metallic chills at regular intervals.

ii. Casting of aluminium alloy.

iii. Evaluation of mechanical properties.

iv. Chemical composition and micro structural examinations of the cast alloys.

v. Structure – property correlation.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Introduction

Pure aluminum is a soft, durable, lightweight, malleable, silverish white metal. Aluminium base alloys find extensive application in automobile industry, air craft industry and other general engineering industries due to their good corrosive resistivity and good strength to weight ratio (Sarada *et al.,* 2013). In most cases, superior mechanical properties are needed for numerous applications, so the performance of the alloy has been the subject of many mechanical investigations. Since strength and hardness of the alloys are mainly depended on their microstructure, a lot of efforts have been done for refining microstructure of castings in order to improve the mechanical properties of the alloys.

Addition of modifier and refiner to the melt is the common method, which in general, is adopted by many researchers (Sarada *et al.,* 2013). Zhang *et al.* (2007) in their work reported that power ultrasound and electromagnetic stirring have been used to refine microstructure of the alloys. Equal-channel angular pressing (ECAP) (Chang and Shan, 2003) and accumulative roll bonding (ARB) (Xing *et al.,* 2001) have also been used to refine microstructure of the aluminium alloy. The water-cooling copper mould (WCCM) casting (Zhang *et al.,* 2007) and the use of chill materials to enhanced solidification rate (Reddy and Pal, 1974) are effective ways of refining microstructure. The methods mentioned above have been done by many researchers in recent years and effects on refining microstructure are acquired at some greater extent.

During casting, heat transfer occurs from the hot liquid metal to the cooled mould and the temperature decreases from that of the cast to the surrounding temperature. The process involves three successive stages; the cooling of the liquid metal, the solidification and finally the cooling of the solid metal (Eman, 2011). The process of solidification; the change of liquid to solid metal after pouring into the mould is the defining event in the life cycle of a casting. The times involved in this activity may be as short as seconds or as long as hours depending upon the casting process and the size of the casting, the chemical composition of the metal being cast, the manner in which solidification occurs (Eman, 2011). The subsequent solid state treatment determines the ultimate microstructure and therefore the properties (mechanical and physical) of the casting.

Areas of the casting that cool rapidly generally have a more favorable grains structure, with less deposition of partially soluble compounds at the grain boundaries. Therefore, these areas tend to have better material properties such as strength, elongation and hardness. Those areas of the casting that cool more slowly generally tend to have poorer material properties. The dendrite cell size, which is controlled by solidification rate, is also an important indicator of the mechanical properties of the casting aluminum alloys (Zhang *et al.,* 2008).

Therefore it is the duty of the metal casting engineer to control the solidification event to the best of its ability so that the microstructure of the final product can be controlled to optimize the properties desired.

There are two categories of chills that are used; internal and external chills.

i. Internal Chills: These are of the same material as the molten metal. They are placed in the mould cavity before molten metal enters into the mould cavity (Ahmad, 2008). Internal chills are set so they project into the mould cavity. They are expected to fuse with the solidifying metal and become a part of the casting (Radhakrishna and Sheshan, 2000).

ii. External Chills: These are inserts placed in the mould to increase the freezing rate of the metal. Their size is determined by the cooling requirements. Steep thermal gradients are established which promote directional solidification and the incidence of macro and micro porosity is reduced (Simpson, 1997). External chills for aluminum castings can be made from cast iron, bronze, brass, silicon carbide, copper, or steel.

Chills are occasionally coated with plumbago, lampblack, red oxide, or other compounds to prevent the cast metals from sticking to them, but this procedure is generally not necessary. Organic coatings should never be used on chills for aluminum alloys. The chills should be absolutely dry (and preferably warm) before being set them in the mold (Joel, 2001). The effects caused by chills are (Adedayo, 2011);

i. Setting up of steep temperature gradient.
ii. Promotion of good directional and progressive solidification.
iii. Reduces incidence of macro and micro porosity.

Chills can be made of many materials, including iron, copper, bronze, aluminium, graphite, and silicon carbide. Other sand materials with higher densities, thermal conductivity or thermal capacity can also be used as a chill. For example, chromite sand or zircon sand can be used when moulding with silica sand.

Liquid metal enters the mould via gravity or low pressure. Pouring of the metal and movement of the mould are coordinated to avoid turbulence when the metal enters the mould. Because molten metal flows into all parts of the mould by gravity and atmospheric pressure, each casting is dimensionally accurate and of reduced porosity. After each casting, the mould is cooled to create a significant temperature difference between the liquid metal and the mould. This temperature difference causes a fine, dense grain structure. The high-quality chill castings offer designers, engineers, and manufacturers many advantages including (Peter, 2001);

- Dimensional uniformity
- Improved mechanical properties
- Pressure tightness
- Close tolerances
- Dimensional accuracy
- Precision and dimensional repeatability
- Bright, smooth metallic surface.
- Fine grain structure.

2.2 Sand Casting Process

Sand Casting is simply melting the metal and pouring it into a preformed sand cavity, called mould, allowing the metal to solidify and then breaking up the mould to remove the cast metal. In sand casting expandable moulds are used. So for each casting operation new mould is formed. The basic Requirements for metal casting are (Liu, 2008);

i. Pattern Making/core box making

ii. Core Making

iii. Sand moulding

iv. Melting and pouring

v. Cleaning/Finishing

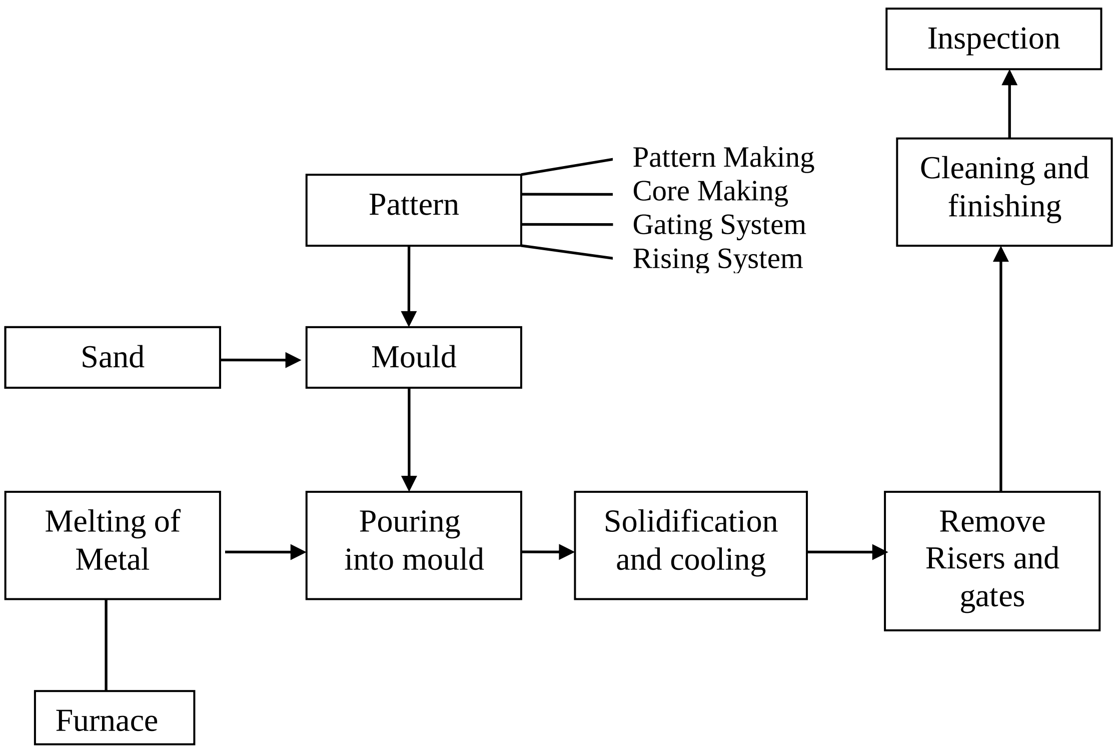


Figure 2.1: Production steps in a typical sand casting (Liu, 2008).

2.2.1 Sand Selection

Several factors are important in the selection of sand for moulding, and it involves certain tradeoffs with respect to properties. Although fine-grained sand enhances mould strength, the fine grains also lower mould permeability. Good permeability of moulds and cores allows gases and steam evolved during the casting to escape easily. The mould should have good collapsibility to allow for the casting to shrink while cooling and, thus to avoid defects in the casting such as hot tearing and cracking (Liu, 2008).

2.2.2 Parting line

Parting line is the line or plane separating the upper and the lower halves of moulds. In general, the parting line should be along a flat plane rather than be contoured. Whenever possible, the parting line should be at the corners or edges of castings rather than on flat surfaces in the middle of the casting. It should be placed as low as possible for less dense metals and located at around mid-height for denser metals (Liu, 2008).

2.2.3 Pattern Making

The pattern is a replica of the object to be cast, used to prepare the cavity into which molten material will be poured during the casting process. Materials used to make patterns include wood, plastics, aluminum, fiberglass, cast iron and some other metals. Wood is preferable because it is easily worked into shape and is not very expensive compare to other pattern materials. During the design process of pattern, some considerations should be taken. For example, the pattern needs to incorporate contraction allowances, which are suitable allowances for shrinkage. And also it needs to incorporate suitable allowances for draft. If the casting is to be hollow, as in the case of pipe fittings, additional patterns; referred to as cores are used to form these cavities (Ibhadode, 1991). The Tables 2.1 and 2.2 show shrinkage allowance and pattern machine finish allowance respectively for machine components of cast aluminium alloys.

Table 2.1: Pattern shrinkage allowance

Casting alloy	Pattern Dimension (mm)	Type of Construction	Section Thickness (mm)	Contraction (mm/mm)
Aluminium	UP to 1220	Open Construction		0.01302
	From 1245-1830	- -		0.01172
	Over 1830	- -		0.01042
	UP to 610	Cored Construction		0.01302
	Over 1220	- -		0.01172-0.01042
	635 to 1220	- -		0.01042-0.00521

Source :(Heine *et al.*, 1976)

Table 2.2: Pattern machine finish allowance

Casting alloys	Pattern size (mm)	Bore (mm)	Finish (mm)
Aluminium alloy casting	Up to 300	2.5	1.5
	330-610	5	3
	635-915	5	4
	Over 915	Special Instructions	Special Instruction

Source: (Heine *et al.,* 1976)

Special coating which prevent the destruction patterns are often applied. Patterns also have some identifiers such as colours on them, each of which has different meaning that represent different treatments and requirements for the patterns. The colour-coding for patterns in sand casting are as follows (Peter, 2001);

i. Red indicates that the surface of the material should be left as it is after casting.

ii. Black indicates that the surface needs core and shows the position of the sand core.

iii. Yellow indicates that the surface needs machining.

2.2.4 Core Making

Cores are usually made of sand, which are placed into a mould cavity to form the interior surfaces of castings. Thus the void space between the core and mould-cavity surface is what eventually the casting becomes. After solidification of casting, the core will be broken to create the required cavity. The Figures 2.2 shows the schematic illustration of sand cores.

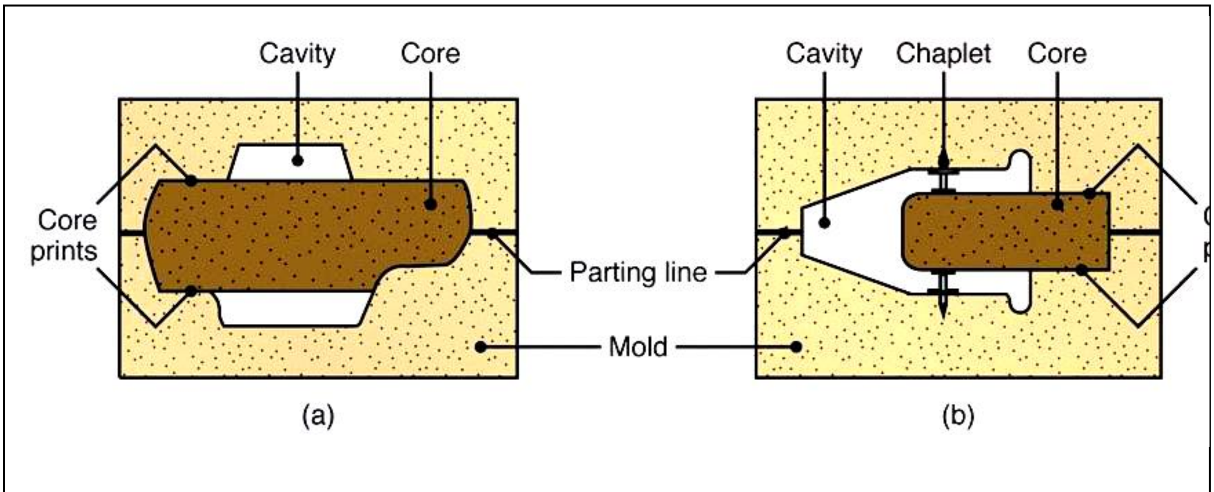


Figure 2.2: Schematic illustration of sand core (Liu, 2008).

2.2.5 Moulding

Moulding consists of placing refractory moulding aggregates around the pattern, which is surrounded by a moulding flask; known as a casting flask, the top and bottom halves of which are known respectively as the cope Mould Moulding boxes are made in segments that may be latched to each other and to end closures. The sand is packed in through a vibratory process called ramming and, in this case, periodically screeded level. The surface of the sand may then be stabilized with a sizing compound. The pattern is placed on the sand and another moulding box segment is added. Additional sand is rammed over and around the pattern. Finally a cover is placed on the box and it is turned and unlatched so that the halves of the mould may be parted and the pattern with its sprue and vent patterns removed.

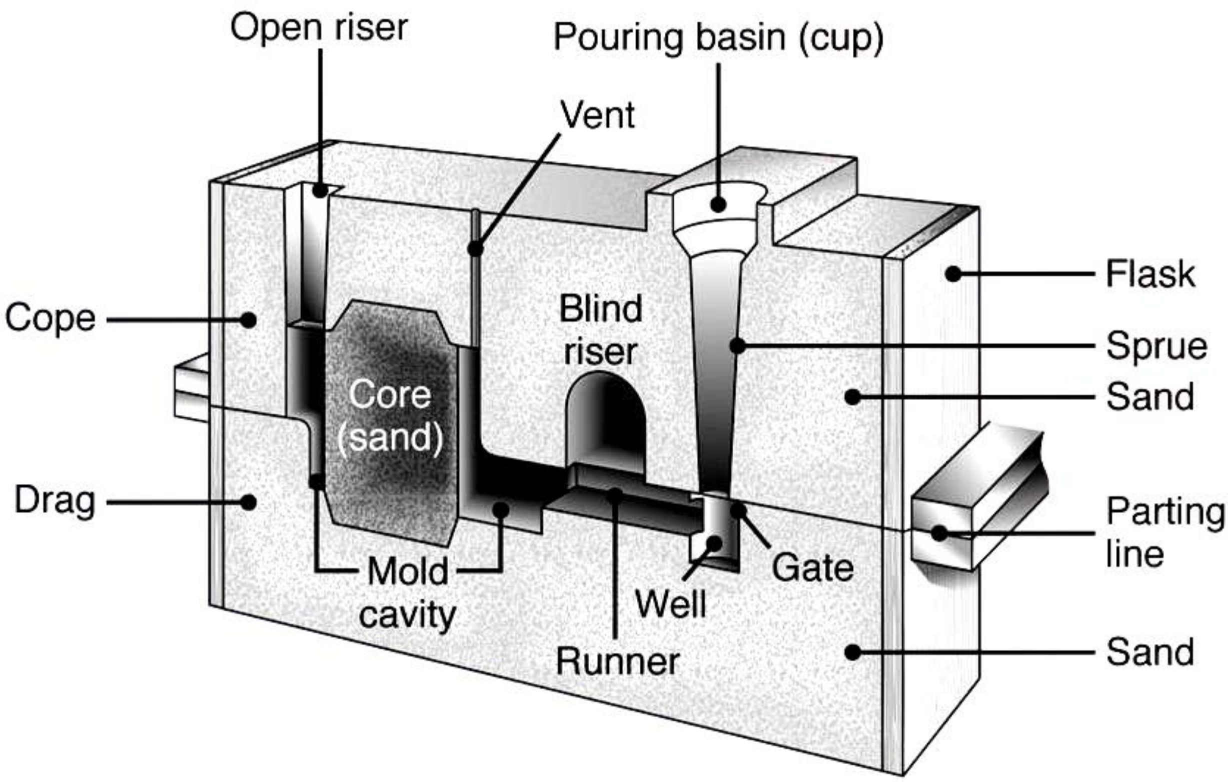


Figure 2.3: Schematic illustration of a sand mould (Liu, 2008).

2.2.6 Melting and Pouring

Melting refers to all the operations carried out to obtain molten metal for casting. This involves melting in a furnace and refining the melt, if the need exists (Ibhadode, 1991). The pouring temperature and method of pouring also contribute to the soundness of casting. Aluminum and its alloys should be poured at a little temperature above its melting point in order to avoid misruns. For any given alloy, the pouring temperature is one of the factors that will determine whether a casting will have a fine grain structure and good mechanical properties or a coarse grain structure and poor properties. A high pouring temperature will tend to solidified into large grains size, whereas a low pouring temperature will tend to formed small grains size (Peter, 2001).

Because molten aluminum absorbs gases easily, pouring is done with the lip of the ladle as close as possible to the sprue of the mould. The stream of molten metal should be kept as large as possible as the sprue will handle. A thin stream or trickle of molten metal from a ladle that is held high above the mould will cause a gas pickup and unnecessary agitation of the metal (Peter, 2001).

2.2.7 The Start of Solidification

After molten metal is poured into a mould, solidification takes place. In the casting process, solidification plays a critical role because the speed at which solidification occurs largely determines the mechanical properties of the casting. The faster the solidification rate, the finer the solidified structure and the higher the mechanical properties. Solidification normally begins on the surface of the casting and moves inward toward the center of the casting or toward the source of feed metal. So solidification can take place in two directions in the casting (Liu, 2008). One is called progressive solidification occurring from the sidewalls of the casting toward the center. The other is called directional solidification occurs toward the source of feed metal. If progressive solidification moves faster than directional solidification, shrinkage voids will occur in the casting. The Figure 2.4 illustrates this kind of shrinkage (Liu, 2008).

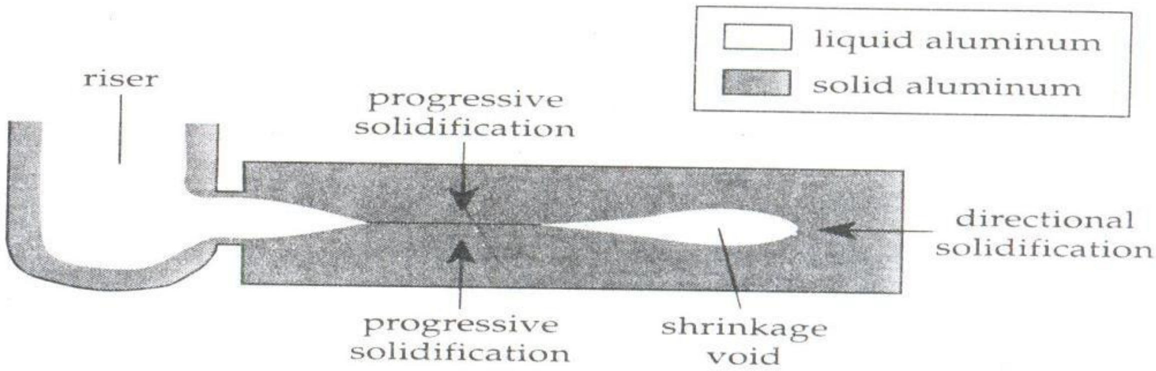


Figure 2.4: Shrinkage caused by progressive solidification.

2.2.8 Riser Design

A riser is an additional larger cast piece which will cool more slowly than the place where it is attached to the casting. Risers are used to compensate for liquid shrinkage and solidification shrinkage. But it only works if the riser cools after the rest of the casting. Where heat should be removed slowly from the molten metal, a riser or some padding may be added to a casting. Generally speaking, an area of the casting which cooled quickly will have a fine grain structure and an area which cools slowly will have a coarse grain structure.

Chvorinov's rule states that the solidification time, t of molten metal is related to the constant, k (which depends on the thermal properties of the mould and the material), the volume, V and the surface area, A of the material, according to the relationship (Peter, 2001)

$$t = k (V/A)^2 \quad \ldots 2.1$$

Therefore, to ensure that the casting solidifies before the riser, the ratio of the volume to the surface area of the riser should be greater than that of the casting. The riser must satisfy two requirements: it must be large enough so that it solidifies after the casting (i.e. satisfies Chvorinov's rule) and it must contain a sufficient volume of metal to supply the shrinkage contraction which occurs on cooling from the casting temperature to the completion of solidification (Liu, 2008). Hence the casting should be designed to produce directional solidification which sweeps from the extremities of the mould cavity toward the riser (Liu, 2008).

2.2.9 Cleaning

Cleaning consist of all the operations carried out to remove sand, scale and excess metal from the casting. The casting is knocked out of the mould, burned-on sand and scales are removed by sand blasting or by other suitable means and excess metal comprising gates, risers and fins are cut off. The casting is inspected for flaws and if defective, it may be salvaged by welding or other means of repair. After the quality control tests, the casting is ready for shipment or further processing such as heat treatment, surface treatment, or machining (Ibhadode, 2001).

2.2.10 Quality Problems in Sand Casting Process

During the metal casting process, some defects may be developed. It is important to improve the casting quality by eliminating or minimizing the effects caused by those defects. Two common defects in sand casting process are caused by porosity and incomplete filling. Porosity may be the most persistent phenomenon in casting, and it is hard to be eliminated completely. Porosity is harmful to the ductility of the casting and its surface finish. Porosity in castings is due to bubbles being trapped during solidification. It may be caused by shrinkage, gases or both. There are many factors that contribute to the development of porosity in casting and these are entrapped air during filling, blowholes from unvented cores, dissolved gases from melting etc. Because liquid metals have much greater solubility for gases than solid metals, when metal begins to solidify, the dissolved gases are expelled from the solution. It will cause microporosity or accumulate in regions of existing porosity (Liu, 2008).

Defects in castings do not just happen. They are caused by faulty procedure in one or more of the operations involved in the casting process, the equipment used, and the design of the part. A casting defect is often caused by the combination of these factors which makes rapid interpretation and correction of the defect difficult.

The defects in casting include blow hole, shrink or shrinkage cavity, buckle and scab, misrun or cold shut, metal penetration, sticker, cut or wash, swell, hot cracks or hot tears, inclusion or dirt etc (Peter, 2001).

2.3 Application of Chills

The casting process is the most flexible, versatile and usually the simplest and least expensive among the number of manufacturing processes. The primary and the most important aspect to be considered in a casting process is the solidification of the casting because solidification shrinkage contributes substantially to the problems faced during the feeding of castings. In case of sand moulds pasty zones pose severe problems; the solution to the problem should aim at establishing a steep temperature gradient during solidification. This can be done by incorporating chills located at predetermined places in the mould. However the use of chills in the mould seems to be the most popular and the simplest way of establishing a steep temperature gradient in the casting during solidification. The chills acts as a heat sink through which heat transfer takes place when placed judiciously in the mould; the chill will establish a steep temperature gradient along the desired direction and in the desired location (Joel, 2001).

As a consequence of using chills, the solidification conditions are altered and so also are the casting properties. Especially in the long freezing range alloys where solidification takes place mainly through mass feeding, chills are highly essential to set up steep temperature gradients (Hemanth, 1999).

2.3.1 Types of Chills

Chills are metallic or non-metallic materials inserted into the mould to promote high solidification rate. They can be machined or cast and are usually made from the following materials (Joel, 2001).

- Cast iron
- Steel
- Copper
- Aluminium
- Graphite
- Silicon carbide
- Brass

The variation between chilled and unchilled mechanical properties tends to be greater in long freezing alloys. This occurs because the chilling improves directional solidification and therefore feeding of the alloy. The resultant improvement in soundness contributes to the improvement in mechanical properties.

2.3.2 Volumetric Heat Capacity (VHC) of Chills

The ability of the chill to extract heat from the molten metal during freezing of the casting is dependent on the size of the chill and thermo-physical properties of the chill material (Joel, 2001). In other words, the capacity of the chill to absorb heat from the casting is taken as a measure of its efficiency. The volumetric heat capacity of the chill, which takes into account the volume, specific heat and density of the chill material, has been identified as an important factor in evaluating the efficiency of the chill.

$$VHC = V x C\rho x \rho \qquad \text{2.1}$$

where V is the volume of the chill, Cρ is the specific heat of the chill material, and ρ is the density of the chill material (Joel, 2001).

It is obvious that a higher value of any of the factors V, Cρ and ρ will increase the value of VHC, thus enhancing the chilling power. When casting the metal in a mould with a chill, heat transfer takes place by conduction through metal-chill interface during the initial stages of solidification. Subsequently, an air gap is formed between the casting and the chill, causing a temporary delay in heat transfer (Syed *et al.,* 2014). In the final stages of solidification, unobstructed heat transfer again takes place when the air escapes from the air gap and there is direct contact between the casting and the chill surface (Syed *et al.,* 2014). In the final stages, the heat transfer takes place again in direct contact with casting and the chill surface. The thermo-physical properties of some commonly used chill materials are given in Table 2.3 (Joel, 2011).

Table 2.3: Thermo-physical properties of chill materials

Chill material	Density (g/cm^3)	Specific heat (kJ/kg^0K)	Thermal conductivity (W/m^0K)	VHC for (170x35x25)mm chill (J^0K)
Copper	8.96	0.448	1.022	597.0
Steel	7.85	0.421	0.109	491.0
Cast iron	7.61	0.401	0.160	453.9
Aluminium	2.75	1.017	0.569	416.0
Graphite	1.62	1.580	0.250	380.7
Silicon carbides	2.36	1.095	0.031	384.3

Joel, 2001

2.4 Review of previous works/Researches

One of the most important phases in a casting process is the solidification of metal in the mould. Since aluminium alloys freeze over a wide range of temperature, they are susceptible to various casting defects such as porosity, cracks, blow holes etc (Syed *et al.,* 2014). Aluminium silicon alloy castings using sand moulds face porosity problem in the form of micro shrinkage. The micro shrinkage can be minimized by incorporating chills (which act as heat sinks) located at predetermined places in the mould (Radhakrishna and Sheshan, 2000). Chilling reduces grains of the alloy to an interface controlled structure, to obtain a material with new functional properties. Hardness and fracture toughness of aluminium alloy significantly dependent on processing routes, dispersoid content, chill conditions, microstructure, and interfacial bonding characteristics (Syed *et al.,* 2014). The following researches have carried out works to investigate the effectiveness of chills in casting of metallic alloys:

David, (2011) investigated the effect of chills and riser placement on mechanical properties of premium sand casting and he was able to relate the relationship between soundness, solidification rate and fatigue properties in alloy A206. Ozun *et al.* (2004) investigated the hardness and micro structural characteristics of rapidly solidified Al-8-16%Si alloy. They used rapid solidification by melt-spinning technique to examine the influence of the cooling rate/conditions on microstructure and mechanical properties.

Seyyed and Masoud (2011) studied the effect of three types of fins on local solidification time of casting of A356 and 6069 alloys as well as the effect of moisture content on cooling rate of sand moulds made of carboceramics. Their results indicate that fin affects severely on solidification time and this influence is more severe in castings produced in moulding materials such as carboceramics which can absorb more moisture.

Joel (2001) investigated the effect of chilling on soundness and ultimate tensile strength (UTS) of aluminum–corundum particulate composite. The results of the investigation revealed that chill thickness and chill material significantly affect the strength and soundness of the composite. The soundness of the composite developed is highly dependent on the chilling rate as well as the dispersoid content. An increase in the rate of chilling and dispersoid content of the material both result in an increase in the ultimate tensile strength of the material.

Leela and Sreenivas (2012) evaluated the microstructure and micro hardness of chill cast Al-B_4C composites. They observed that the chill material has a significant influence on the microstructure and hardness of the cast specimens. Finer structure and better hardness were observed with the specimens cast using copper chills, whereas, cast iron and stainless steel chills gave rise to coarse structure with reduced hardness.

Syed *et al.* (2014) studied the mechanical properties (strength and fracture toughness) of chilled Al alloy/Kaolinite/C hybride metal matrix composite. Their results revealed that the fracture toughness of cryogenically chill cast Al-alloy/kaolinite/C hybrid is significantly depending on percentage of dispersoid contents (kaolinite & graphitic carbon), the rate of cooling i.e. chill rate (which in turn depends on the thickness of the chill employed), and the interface. The strength, hardness and fracture toughness properties of the chilled hybrid are superior to those of the unreinforced matrix alloy.

Zhang *et al.* (2008) studied the effect of cooling rate on solidified microstructure and mechanical properties of aluminium-A356 alloy and concluded that the micro hardness increases with decreasing dendrite arm spacing (DAS), i.e. it increases when the cooling rate increases. The reason for this is probably that the larger cooling rate caused an extended solid solution to be formed and refined the microstructure.

Dobrzanski *et al.* (2007) investigated the effect of cooling rate on microstructure and mechanical properties of AC AlSi9Cu alloy, the investigation revealed that increasing cooling rate refines all micro structural features including secondary dendrite arm spacing (SDAS) and intermetallic compounds and improves silicon modification level which in turn improves the mechanical properties.

Ramin (2001) carried out an investigation on the effect of mould materials on solidification, microstructure and fluidity of A356 alloy in lost foam casting. He successfully derived the correlation between DAS and local solidification time for the A356 alloy in different mould media. The smallest DAS size was obtained in steel shot mould while the largest was in mullite mould. Furthermore, the DAS size close to the edge of the samples is finer compared to those in the center of the casting. Finally, the effect of the cooling rate on dendrite arm spacing of the A356 alloy in different mould materials and thicknesses of casting were evaluated.

An investigation was carried out on the effect of cooling rate on $Mg_{17}Al_{12}$ volume fraction and compositional inhomogeneity in a sand-cast AZ91D magnesium plate by Chi-Yuan *et al.* (2006). An evident of cooling rate gradient with respect to distance from riser during solidification in a sand-cast AZ91D plate was obtained via putting a chill block at one end of the mould cavity. However, almost no cooling rate fluctuation occurred in the plate without the chill block.

Investigation of chills on aluminium 4.5 percent copper alloy casting soundness was conducted to studied the influence of end chill of varying volumetric heat capacity (VHC) on bar type castings of the alloy by Reddy and Pal (1974). They established that the rate of heat extraction of the chills depends on the VHC of the chill materials and their presence greatly improves the mechanical properties.

Prakash and Rajesh (2014) reported an experimental investigation on the heat transfer coefficient (HTC) during sand casting of A356 alloy by evaluating the effect of chill material and size. It was found that copper chill have the greater cooling effect, ranging from 4 to 8 kW/m^{o}K depending on the size, aluminum chill range from 3 to 6 kW/m^{0}K, gray cast iron range from 1 to 2 kW/m^{o}K. Copper chill size has a direct effect on HTC value, while aluminum and cast iron chills showed an inverse correlation between size and HTC.

The quantitative assessment of the effect of copper chills on casting/chill interface behaviour and the microstructure of sand cast A319 Alloy was reported by Mehr (2012). The use of chills as a means of influencing solidification in lost foam cast aluminium alloy A356 was studied by Simpson (1997). Their investigations conducted independently affirmed the influence of chill materials in enhancing directional solidification which improve the microstructure of the alloy and its mechanical properties.

The present work tends to study the influence of different metallic materials as chills in sand casting of aluminium silicon alloy by arranging the chills at regular intervals round the sand mould. The extent of cooling imparted by the chill materials will be investigated and the micro structural evolution and mechanical properties would also be evaluated.

CHAPTER THREE

3.0 MATERIALS AND METHODOLOGY

3.1 Materials

The materials used in this research work include;

i. Aluminium alloy scrap: Aluminium alloy scrap was obtained from pantaker (a spare part market) in Kaduna metropolis.
ii. Chills: Mild steel, brass and copper chills were used in this research work.
iii. Foundry sand: Foundry sand and other additives used in the present investigation were made available in metallurgical and Materials engineering foundry workshop of Ahmadu Bello University, Zaria.

3.2 Equipment

i. Furnace: The melting of the alloy was carried out on charcoal fired furnace available in metallurgical and Materials engineering workshop.

ii. Vicker Hardness Tester: Vicker Hardness machine of capacity 10 kg was used to carried out the hardness test of the samples.

iii. Charpy Impact Tester: Impact test was carried out on a Charpy Impact Testing Machine of capacity 25J.

iv. Optical Metallurgical Microscope: Microstructural examination was conducted on optical metallurgical microscope available at Metallurgical and Materials Engineering work shop.

v. Hounsfield Tensometer: Tensometer machine in Mechanical Engineering workshop was used to carry out tensile test for the samples.

vi. Thermocouples: Thermocouples were employed in the measurement of temperature gradient of the solidifying metal during casting operation.

3.3 Experimental Procedures

The experimental procedures of this study consist:

3.3.1 Casting of Alloys

Four samples of the aluminium silicon alloy were cast by melting the spare part scrap on charcoal fired furnace using four different sand moulds where three of the moulds were inserted with steel, brass and copper chills respectively and the fourth one without chill which serve as control. The castings were labeled as samples A, B, C and D accordingly. The sample geometry is 165mm x 80mm x 10mm and the chill is of cylindrical shape of diameter 7mm with length 50mm. There are 10 pieces of chills in each mould and the chills were arranged side by side at regular intervals of 30mm. The fluxing and degassing were done before the molten metal was poured into the moulds cavity. The rates of cooling (temperature gradient) were studied with the aid of thermocouples attached to the sand mould immediately before the pouring of the molten metal. The arrangement of the chills within the sand mould is shown in Figure 3.1 whereas sand mould without chill is shown in Figure 3.2. Figure 3.3 display cast metal in sand mould with thermocouples and the chemical composition of the sample is presented in Table 3.1.

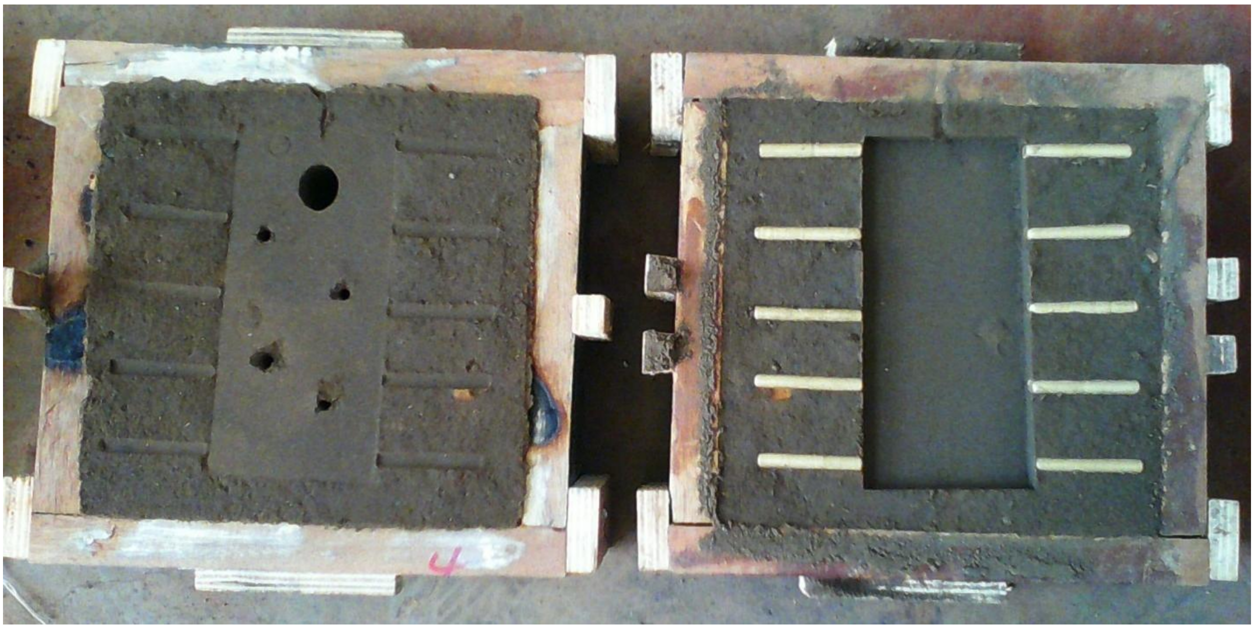


Figure 3.1: Sand mould with chills

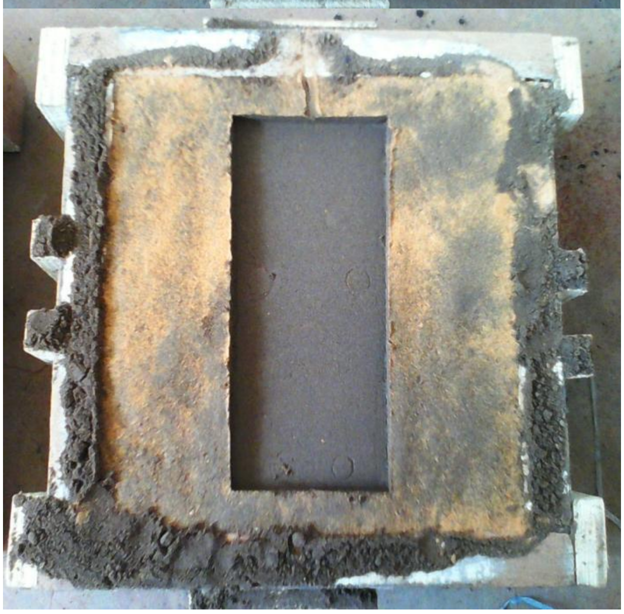


Figure 3.2: Sand mould without chill

Figure 3.3: Cast metal in sand mould with thermocouples

Table 3.1: chemical composition of the cast aluminium alloy

Al	Si	Mg	Fe	Cu	Mn	Zn	Ti
90.742	7.155	0.388	0.359	1.228	0.054	0.008	0.066

The chemical analysis of the cast samples was conducted in the Tower Aluminium Rolling Mills Industry, Ogun State using Optical Emission Spectrometer.

3.3.2 Tensile Strength Test

The tensile test specimens were machined from the cast samples. The test piece was locked securely within the grips of the Tensometer machine. The test piece was stretch with force generated from manually operating the screw attached to the Tensometer until the test piece broke apart. The load and extension data available from the graph sheet attached to the machine were converted to specific values of stress and strain. The geometry of the tensile test sample is shown in Figure 3.4

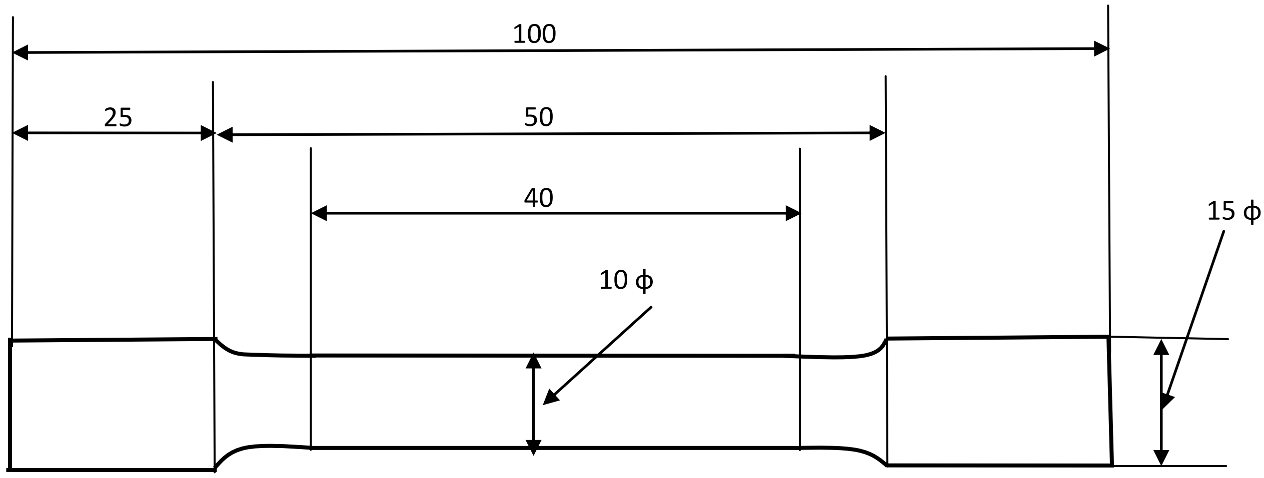


Figure 3.4: Dimension of the tensile test sample (mm)

3.3.3 Hardness Test

Hardness test was carried out on Vicker Hardness testing machine. An indentor was placed above the sample flat surface. A load of 50gm was applied on the indentor for about 10-seconds which then penetrates the surface of the sample and the hardness value is displayed on the machine. Three different indentations were made on a sample and the average is taken as the hardness value of the samples. This procedure was repeated for the remaining samples.

3.3.4 Impact Strength Test

Charpy Impact Testing machine was employed in conducting the impact test of the samples. A V-notch was machined into a 10mm wide and 100mm long test pieces with the notch depth of 4mm. The specimen was placed across parallel jaw of the testing machine and a heavy pendulum, released from a known height, struck and broke the test piece. This measured the energy necessary to fracture the standard notch test piece by an impact load and the dial pointer of the scale on the machine indicates the energy absorbed, in Joules, by the test piece from the impact. The value of the energy absorbed in breaking the test piece was recorded for the whole samples.

3.3.5 Metallographic Examination

Four specimens were prepared from the four aluminium alloy samples for metallographic examination. The procedure consists of cutting, successive grinding using silicon carbide grit paper of 240, 320, 400 and 600 microns. Polishing was carried out on a rotating cloth to ensure mirror-like surface. A solution containing 5ml nitric acid, 2ml hydrofluoric acid and 100ml of distilled water was used to etch the specimens for about 10 seconds. The specimens were observed under Digital Metallurgical Microscope where the micrographs of the specimens were recorded at a magnification of 100X.

CHAPTER FOUR

4.0 RESULTS AND DISCUSSION

4.1 Results.

The results of the tests carried out are shown in table 4.1-4.3 and figure 5.1-5.4

Table 4.1: Solidification rates of aluminium alloy

Time (min)	Sample A (J/min)	Sample B (J/min)	Sample C (J/min)	Sample D (J/min)
0	503.0	479.0	472.5	490.5
4	495.0	452.7	419.2	473.2
8	461.3	429.2	383.1	438.9
12	423.2	398.4	351.3	404.8
16	387.0	366.9	324.0	382.7
20	358.4	339.6	303.0	358.8
24	334.3	317.2	285.0	337.1
28	315.2	299.1	270.0	318.9
32	299.6	284.0	258.0	302.4
36	286.5	272.0	247.7	287.0
40	276.0	262.3	240.0	277.1
44	265.5	252.7	232.3	266.3
48	258.4	246.4	226.7	258.3
52	251.1	239.5	221.6	251.5
56	245.2	233.7	216.9	244.3
60	239.2	228.8	212.5	238.4

Samples: A- steel chill, B- brass chill, C- copper chill and D- no chill.

4.2 Mechanical Properties of Aluminium Alloy

The results of ultimate tensile strength, hardness values and impact strength of the samples are presented in Tables 4.2.

Table 4.2: Mechanical properties of aluminium alloy

Samples	Ultimate tensile strength (MPa)	Hardness (Hv)	Impact Strength (J)
A	101.33	5.40	22.7
B	115.83	5.73	22.4
C	126.13	6.87	23.5
D	70.67	4.2	22.5

4.3 Micro structural Evolution of Aluminium Alloy

The micrographs of the cast aluminium alloy samples are presented in Plate 1.

4.4 Volumetric Heat Capacity (VHC) of the Investigated Chills

Table 4.3 shows the thermo physical properties of the chill materials used for the present investigation.

Table 4.3: Thermo physical properties of chill materials

Chill material	Density (kg/m^3)	Specific heat (J/kg^0K)	Thermal conductivity (W/m^0K)	VHC for $1925mm^3$ chill ($J/^0K$)
Steel	7850	421	50.2	63.62
Brass	8550	380	109	62.54
Copper	8960	448	401	77.27

CHAPTER FIVE

5.0 DISCUSSION OF EXPERIMENTAL RESULTS

5.1 Influence of Chill Materials on Solidification of Aluminium Alloy

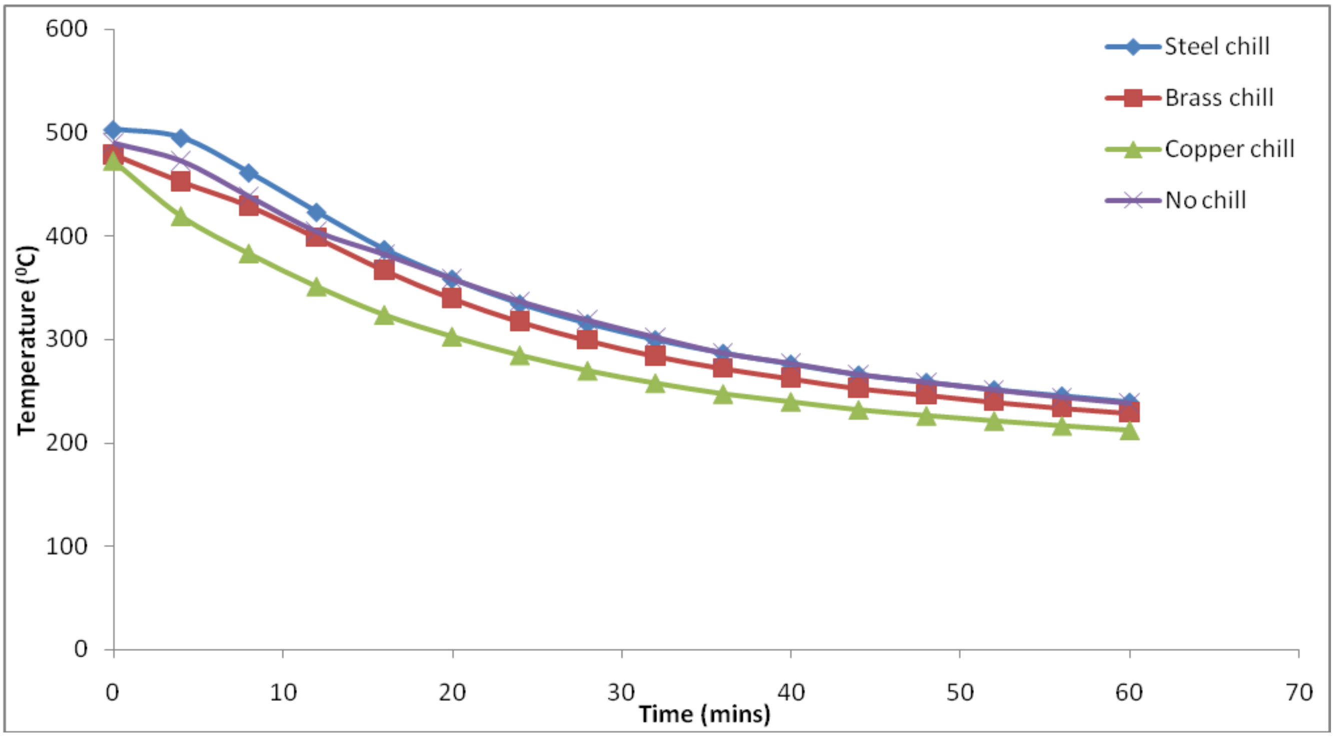


Figure 5.1: Cooling curves of aluminium alloy during solidification

Cooling rate plays an important role in determining the microstructure of the casting. Higher cooling rate reduces solidification time and grain size of the casting. This may be attributed to the solidification process of aluminium alloy where a high percentage of solids are formed during the earlier stages of freezing and is followed by a pasty mode of solidification with non-equilibrium eutectic solidifying at the end. Nucleation initiated at the mould wall, chill surface or at dispersoids and then spreads quickly into the interior of the liquid metal in the mould cavity and crystallization occurs at numerous centers in the liquid as presented by Joel,(2001). Hence, at this stage, a pasty mass of liquid and solid exists along with the fully solid and fully liquid zones containing intermetallic particles.

It is evident from Figure 5.1 that casting with copper chill solidified faster than any other one with other chills. This is followed by brass chill and casting with steel chill almost has the same solidification rate with that of no chill at the beginning but slightly higher than no chill casting towards the end of the solidification. The volumetric heat capacity and thermal conductivity of copper is higher than that of brass and steel which enable the copper chill to extract heat faster than any other chill materials from the melt. The brass is higher than steel in terms of thermal conductivity and this also enhance its heat extraction rate from the melt faster than steel as a chill material. The steel chill shows little heat extraction rate when compared to the casting where chill material is not inserted in the mould. These observations of solidification gradient influence strongly the types of structure and the mechanical properties of the aluminium alloy formed

5.2 Influence of Chill Materials on Ultimate Tensile Strength of Aluminium Alloy

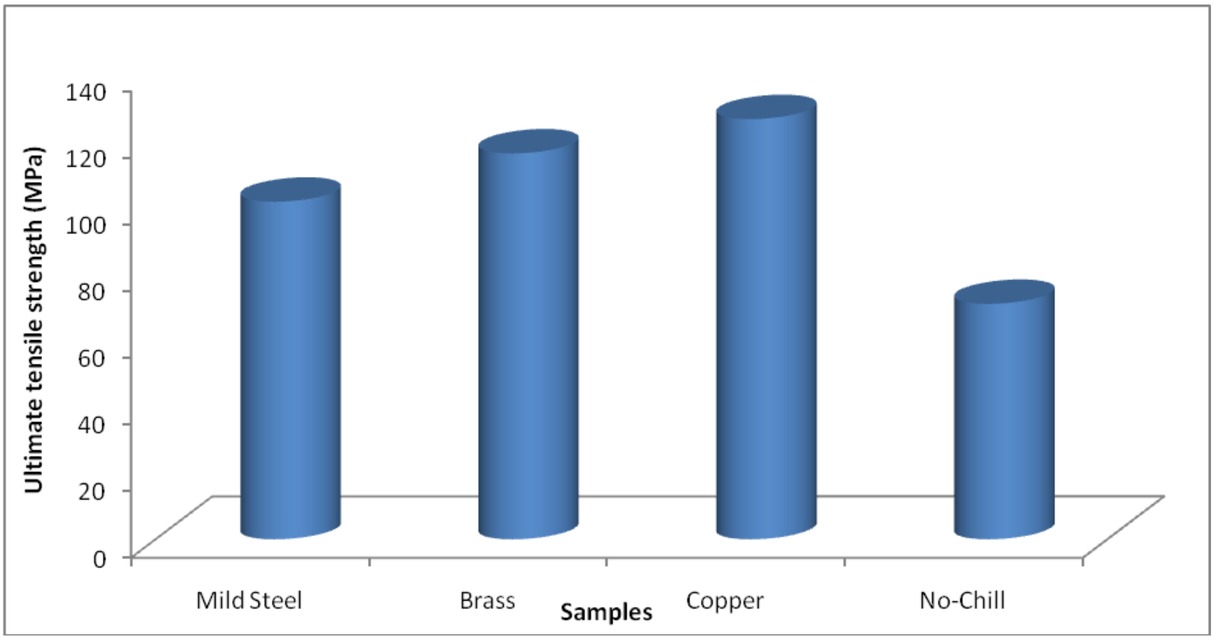


Figure 5.2: Chart of ultimate tensile strength of samples with different chill materials

It is well known (Joel, 2001) that aluminium alloys that freeze over a wide range of temperature are difficult to feed during solidification. The dispersed porosity caused by the pasty mode of solidification can be effectively reduced by the use of chills as presented by Joel (2001). Chills extract heat at a faster rate and promote directional solidification. The casting with copper chill shows the highest ultimate tensile strength followed by the casting chilled with brass (Figure 5.2). This is as a result of high values of thermal conductivity displayed by the copper and brass materials. The casting with no chill material shows the least ultimate tensile strength when compared to the steel chilled casting indicating the essence of presence of chill materials in improving the soundness of the casting.

The reason for these observations is attributed to the types of microstructures formed during solidification. A fine-grained material is harder and stronger than one that is of coarse grain structure, since the former has a greater total boundary area to impede dislocation motion as observed by William (2009). The copper chilled sample are characterized with finer grains structure with uniformly distribution of intermetallic particles due to high heat extraction rate and when this sample was subjected to tensile experiment, the material shows a high ultimate tensile strength before fracture occurred. This trend was also observed in other samples chilled with brass and steel. The ultimate tensile strength of sample with no chill which are predominately characterized with coarse grains structure is very low due to slow cooling rate.

5.3 Influence of Chill Materials on Hardness Value of Aluminium Alloy

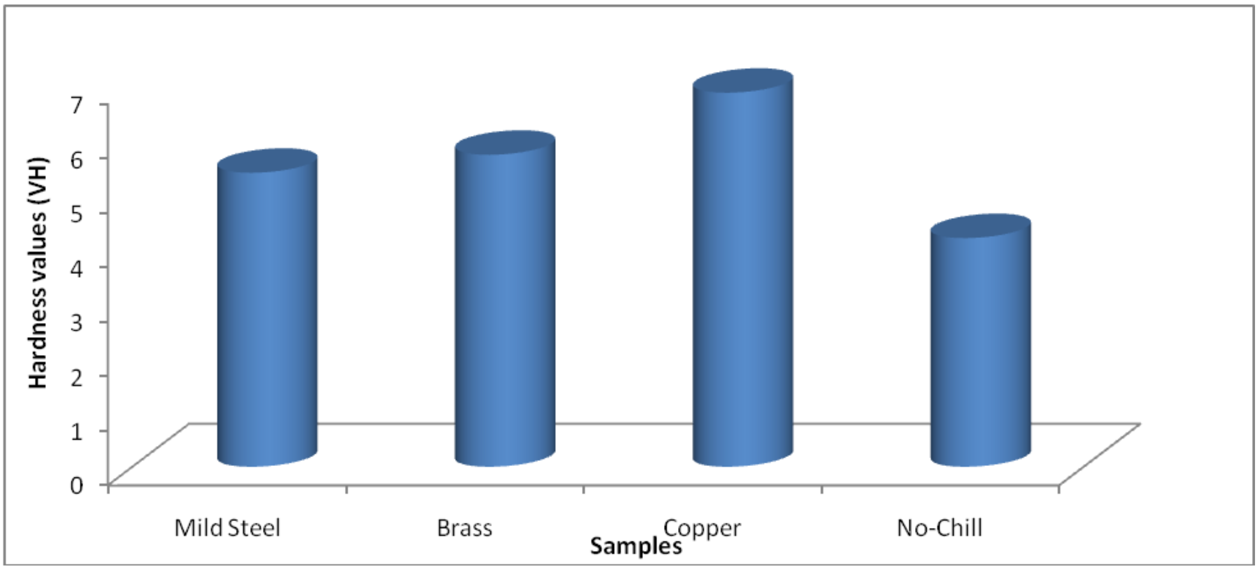


Figure 5.3: Chart of hardness value of samples with different chill materials

The chart of hardness values of samples chilled with different metallic materials (Figure 5.3) revealed that the casting with copper chill displayed the highest hardness value which is closely followed by that of brass chill and then steel chill. The casting with no chill shows the lowest hardness value. This observation agreed with the research finding of Leela and Sreenivas, (2012). This is attributed to the fact that casting with copper chill gives rise to fine grains structure. The microstructure of casting with brass chill is finer than the casting chilled with the steel whereas the casting with no chill material resulted in coarse grains structure. It is well known that coarse grains material is usually lower in hardness value compared to fine grains structure. Therefore the observed trend in hardness values correlates with the microstructure which dictates the mechanical properties the materials.

5.4 Influence of Chill Materials on Impact Strength of Aluminium Alloy

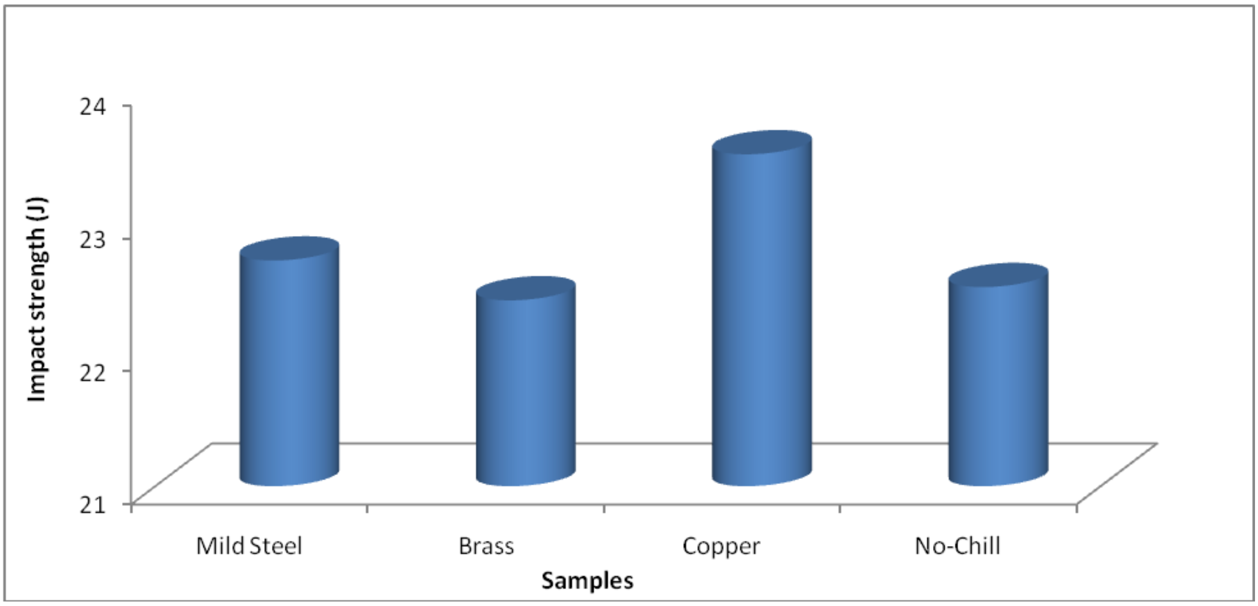


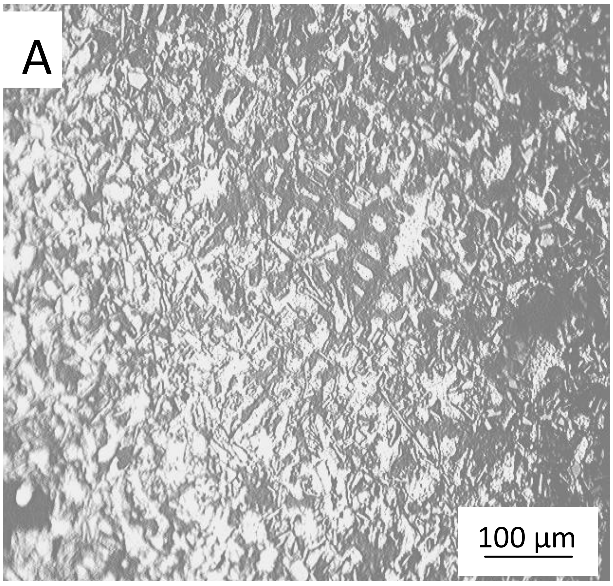
Figure 5.4: Chart of impact strength of samples with different chill materials

The toughness of the material is an integral part of mechanical properties which indicate the material ability to absorb energy in the plastic range. The microstructural evolution of the material is an important parameter that greatly influences the extent at which such material can withstand the impact load without fracture. Figure 5.4 clearly revealed that sample chilled with copper shows the highest toughness value followed by steel chilled sample and the other samples show closely the same values of impact strengths.

A fast cooling rate generally refines the microstructure and increases the solid solubility of the alloying elements in solid solution thereby improving the mechanical properties (Zhang *et al.*, 2008). The grain size and its morphology, dendrite arm spacing (DAS), size and distribution of secondary phases are effective parameters, which control the mechanical properties of casting parts (Shabestari and Momeni, 2004). DAS decreases with increasing cooling rate and casting microstructure will become finer by decreasing DAS (Shabestari and Momeni, 2004). More also, the size of silicon particles and secondary phases become smaller with increasing cooling rate and these improve the mechanical properties of the cast metallic alloys in general (Shabestari and Momeni, 2004).

The increase in cooling rate attributed to the casting with copper chill improved its impact property. The higher value of impact strength recorded for steel chilled sample when compared to brass and un-chilled samples may be due to low levels of inclusions present in the alloy. Inclusions which are the sites of stress concentration increased with slow cooling rate and the other samples fractured easily by the mechanism of coalescence when subjected to impact load. This accounted for lower impact strengths revealed by the brass and un-chilled samples.

5.5 Influence of Chill Materials on Microstructure of Aluminium Alloy



B

100 µm

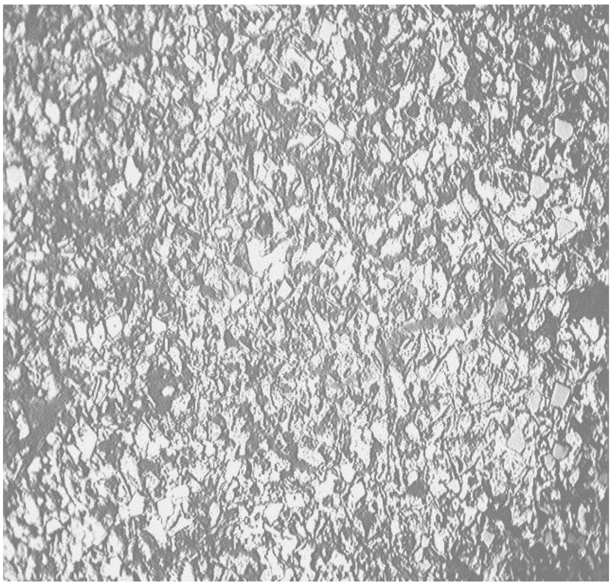
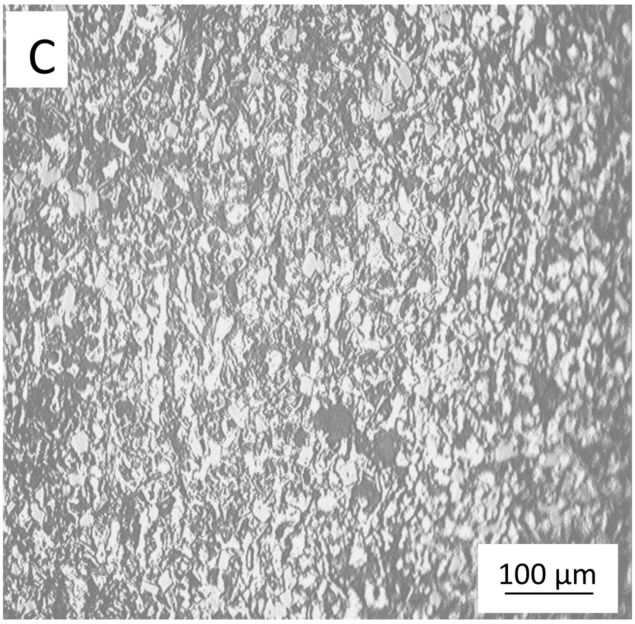


Plate 1: Influence of steel chill microstructure Plate 2: influence of brass chill microstructure



D

100 µm

Plate 3: Influence of copper chill microstructure Plate 4: No chill microstructure

Plate 1-4: Optical micrographs of samples of cast aluminium silicon alloy using different metallic chill materials. Samples: A- steel chill, B- brass chill, C- copper chill and D- no chill. White spots are interdendritic of intermetallic particles distributed in aluminium matrix (black back-ground).

Plate 1-4 show the microstructures of the cast components using steel, brass, copper chills and cast without chill. The microstructures indicate that the chill materials have decided effects on the grain size and also on the distribution of phases in the alloy. When the hot metal comes in contact with the chill materials, the melt experiences severe supper cooling. This results from a high rate of heat transfer of the melt in chilled samples. Hence the critical nucleus size of the solidified melt is reduced and a greater number of nuclei are generated, causing a finer microstructure. Finer grains structure was obtained with the use of copper chill whereas the mild steel and brass chilled castings also displayed fine grains structures but casting with no chill gave rise to coarse grains structure. This is because of the higher rate of heat extraction and faster cooling rate in case of copper chill. Also, the silicon distribution is more uniform in the casting obtained using chill whereas, the silicon tends to agglomerate in the matrix of the castings obtained no chill. The uniform distribution of particles (silicon and other minor elements) and fine matrix structures (Plates 1, 2 and 3) lead to improved mechanical properties of the samples with chills as compared with the un-chilled sample (Plate 4).

CHAPTER SIX

6.0 SUMMARY, CONCLUSION AND RECOMENDATIONS

6.1 Summary

In this research work, effort has been made to investigate the effectiveness of different metallic chills in sand casting of aluminium alloy from their solidification rates, microstructures and mechanical properties points of view. Based on the results obtained, it was observed that copper chill have the highest solidification rate followed by brass chill and the least being steel chill. The casting with no chill exhibits the lowest cooling curve. The mechanical properties also vary directly with the solidification rate.

6.2 Conclusion

From the results and discussion of the study, the following conclusions can be drawn;

- The cast aluminium alloy sample with copper chill displayed the highest mechanical properties (ultimate tensile strength of 126.13mPa, hardness value of 6.87$Hv_{0.05}$ and impact strength of 23.5j respectively) and finer grains structure than any other samples under investigation. The cast sample inserted with brass chill also shows higher values in mechanical properties than sample with steel chill and unchilled sample. The steel, brass, and unchilled samples almost displayed the same impact strength of 22.7J, 22.4J and 22.5J respectively.

- The cast sample inserted with copper chill solidified faster than any other cast sample with chill. The cast sample inserted with brass chill solidified faster than the cast sample with steel chill.
- The coarseness of the grains in the microstructure of these samples also increased from samples chilled with brass, steel and no chill.

6.3 Recommendations

Cooling rate plays an important role in determining the microstructure of the casting. Higher cooling rate reduces solidification time and grain size of the casting. Hence, grain density increases with cooling rate. From previous experimental observation, the average pore size decreases with increased cooling rate and for higher cooling rate, the dendrite arm spacing (DAS) decreases and the pore growth is thus limited (James *et al.*, 2000). Another explanation offered by James *et al.* (2000) is that with decreased solidification time, there is less time for hydrogen to diffuse from the solidifying dendrite to the liquid and hence, gas pore growth rate is inhibited. Therefore any investigation aimed to increase cooling rate is considered vital in metal casting process. The following recommendations were suggested for further research work.

i. The influence of different chill sizes on solidification time and mechanical properties.

ii. Cooling mediums other than air can be investigated.

iii. The effect of heat treatment can also be investigated.

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APPENDIX

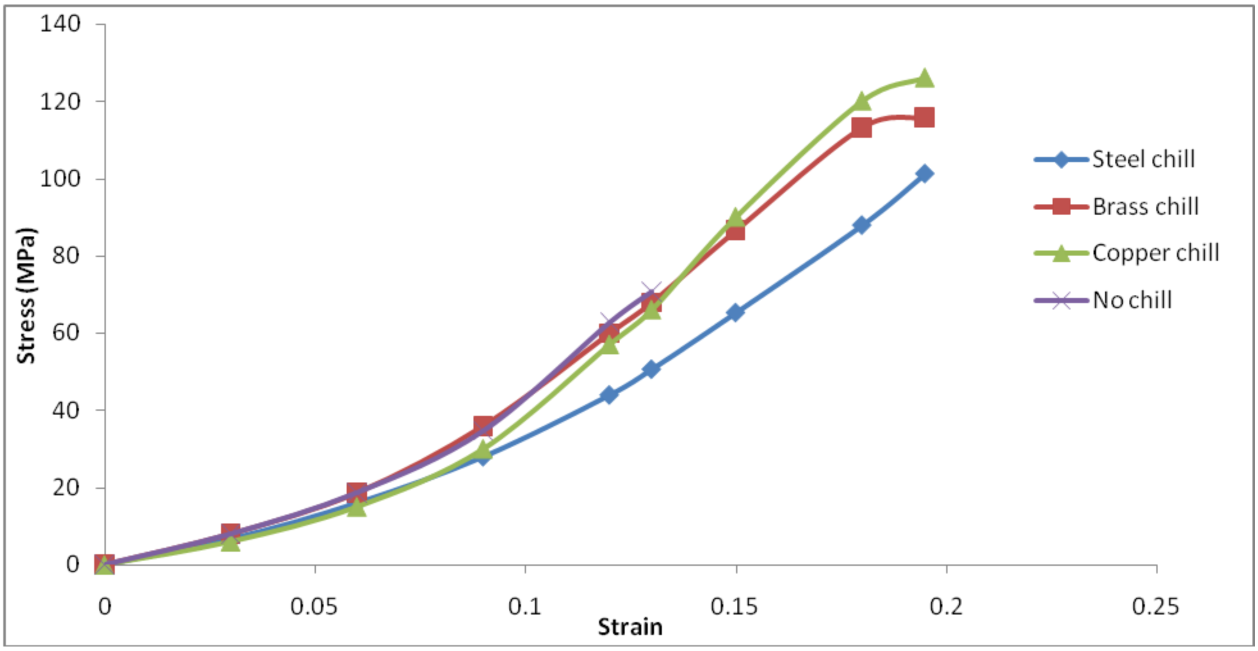

Figure A: Stress-strain curves of the aluminium alloy.