EFFECTS OF COPPER ADDITION AND SECTION THICKNESS ON SOME MECHANICAL PROPERTIES AND THE MORPHOLOGY OF GRAPHITE FLAKES IN GREY CAST IRON

BY

ZAHRADDEEN MUSA

DEPARTMENT OF METALLURGICAL AND MATERIALS ENGINEERING,
FACULTY OF ENGINEERING
AHMADU BELLO UNIVERSITY,
ZARIA, NIGERIA

DECEMBER, 2016

EFFECTS OF COPPER ADDITION AND SECTION THICKNESS ON SOME MECHANICAL PROPERTIES AND THE MORPHOLOGY OF GRAPHITE FLAKES IN GREY CAST IRON

BY

Zahraddeen MUSA, B.Eng. (ABU) 2008

(MSc/Eng/45784/2012-2013)

**A DISSERTATION SUBMITTED TO THE SCHOOL OF POSTGRADUATE STUDIES,
AHMADU BELLO UNIVERSITY,
ZARIA**

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE AWARD OF A MASTER OF SCIENCE DEGREE IN METALLURGICAL AND MATERIALS ENGINEERING

**DEPARTMENT OF METALLURGICAL AND MATERIALS ENGINEERING,
FACULTY OF ENGINEERING
AHMADU BELLO UNIVERSITY,
ZARIA, NIGERIA**

DECEMBER, 2016

Declaration

I declare that the work in this Dissertation entitled 'Effects of copper addition and section thickness on some mechanical properties and the morphology of graphite flakes in grey cast iron' has been carried out by me in the Department of Metallurgical and Materials Engineering under the supervision of Prof. O. Aponbiede and Prof. T. Ause. The information derived from the literature has been duly acknowledged in the text and a list of references provided. No part of this dissertation was previously presented for another degree or diploma at this or any other Institution.

Musa Zahraddeen _____ _____

(Signature) **Date**

Certification

This dissertation entitled 'EFFECTS OF COPPER ADDITION AND SECTION THICKNESS ON SOME MECHANICAL PROPERTIES AND THE MORPHOLOGY OF GRAPHITE FLAKES IN GREY CAST IRON' by Zahraddeen MUSA meets the regulations governing the award of the degree of Master of Science of the Ahmadu Bello University, and is approved for its contribution to knowledge and literary presentation.

Prof. O. Aponbiede _____ _____

Chairman, Supervisory Committee (Signature) Date

Prof. T. Ause _____ _____

Member, Supervisory Committee (Signature) Date

Dr. A. Kasim _____ _____

Head of Department (Signature) Date

Prof. KabirBala _____ _____

Dean, School of Postgraduate Studies (Signature) Date

Dedication

This work is dedicated to my parents, Alhaji Musa A. Kazaure and HajiyaBinta Musa.

Acknowledgement

All praises be to Allah for making it possible for me to successfully complete this research work.

I will like to express my gratitude to my major and minor Supervisors, Prof. O. Aponbiede and Prof. T. Ause, for their insightful guidance and support during the course of this work. May the Almighty God continue to guide and protect you all in good health and wealth ameen. My profound and deepest gratitude goes to my loving parents, Alhaji Musa A. Kazaure (MagatakardanKazaure) and HajiyaBinta Musa. Words cannot express all the support I continuously get from both of you.

I am deeply indebted to Dr. AuwalKasim for his readiness to assist and prompt approval for the use of the laboratory facilities at the Department of Metallurgical and Materials Engineering, ABU, Zaria. My gratitude also goes to Engr. Yakubu Mohammed, Mal. Suleiman, Mal. Yusuf, Mal. Zamani, Mal. Ayuba, Mr. Danladi and Mr. David of the Department for their assistance during the course of the practical works. May Allah reward you all abundantly.

I will also wish to thank Prof. S.A Yaro, Prof. A.K Oyinlola, Prof. E.T Dauda, Dr. F. Asuke, Dr. S. Umar, Dr. M. Abdulwahab, Dr. D. G. Thomas, Dr. R. Mohammed, Engr. J. Gaminana, Engr. I. Usman, Engr. Asma'u G., and Engr. M.R. Dodo for their objective contributions in making this research work a reality.

Lastly I am indeed grateful to my caring wife, Hauwa Y. Muhammad for her patience, and to all my siblings, friends and well-wishers for their supports and encouragement.

Abstract

This study determined the effects of copper addition and section thickness on some mechanical properties and the morphology of graphite flakes in grey cast iron. It also characterised the microstructure of grey cast iron evolved in the investigation. This was of the view of ensuring that automotive industry designers are able to make informed choice between competing materials and grey cast iron, thus reducing the overall cost of the automobile. Four classes of grey cast iron containing 0.02, 0.55, 0.7 and 1.15% amount of copper were investigated. The section thicknesses of the produced grey cast iron were 10 mm, 25 mm and 75 mm respectively. The chemical composition, mechanical properties, graphite flake measurements and microstructural characterisation of each section of the casting were carried out with the aid of optical emission spectrometer, mechanical testing equipment and scanning electron microscope. The 0.7% Cu alloyed grey cast iron with section thickness of 10 mm produced the highest tensile strength of 150.28 N/mm^2, hardness value of 47.5 HRC and the least impact strength of 76.96 kJ/m^2. It was also discovered from microstructural characterisation that 10 mm section thickness has the shortest graphite flake length of 64.32 µm. However, the 1.15% Cu alloyed grey iron with 75 mm section thickness had the least tensile strength of 58.36 N/mm^2, hardness value of 40.1 HRC and the highest impact strength of 107.13 kJ/m^2. This also supported the longest graphite flake length of 105.68 µm. This is attributed to the fact that addition of copper up to 0.7% in grey cast iron enhanced the pearlite phase and promotes the formation of ferrite when increased to 1.15% by weight. The results of microstructural examination revealed that the morphology of the graphite flakes changes from fine and small flakes to coarse and long

flakes as the section thickness increases. The research showed that the developed type B (rosette graphite) flake having 85.95 µm length in the 1.15% Cu grey cast iron with 10 mm section thickness gave a good combination of mechanical properties having 2.85% elongation, 111.41 N/mm^2 tensile strength, 44.4 HRC hardness and 89.65 kJ/m^2 impact strength. It can be concluded that with the set of properties exhibited by the 0.7% Cu grey cast iron with 10 mm section thickness, automobile industry components and farm implements could be produced from this type of grey cast iron.

Table of Contents

List of Tables

List of Figures

List of Plates

List of Appendices

Abbreviations, Definitions, Glossary and Symbols

%	-	Percentage
Mn	-	Manganese
Fe	-	Iron
P	-	Phosphorous
C	-	Carbon
SEM	-	Scanning Electron Microscopy
OM	-	Optical microscopy
Ti	-	Titanium
V	-	Vanadium
S	-	Sulphur
x350	-	Magnification at 350 times
Si	-	Silicon
Cu	-	Copper
µ	-	micro
Al	-	Aluminium
Ni	-	Nickel
α	-	Ferrite
k	-	Kilo
Fe_3C	-	Iron-carbide
Ca	-	Calcium
Ba	-	Barium

CHAPTER ONE

INTRODUCTION

1.1 Preamble

Recent advancements in technology continue to exert a very high demand for light, durable and cost effective materials. This creates the need to look for materials that combine excellent mechanical properties as well as improving those already in service.

Grey cast iron (GCI) is part of a group of materials that can be produced for having a wide-range of properties through controlled microstructure. The as-cast matrix microstructure of grey cast irons is often entirely pearlitic, with graphite lamellas finely distributed in the matrix (Pevec*et al.*, 2014).

Graphite flakes, which are formed during the solidification process, basically control the mechanical properties of the grey cast iron. The amount of graphite and size, morphology and distribution of graphite lamellas are critical in determining the mechanical behaviour of grey cast iron(Collini*et al*., 2008).

The structure of GCI depends on chemical composition before the casting process, inoculants and cooling conditions (Collini*et al*., 2008). Slow cooling promotes graphite formation whereas rapid cooling partly or completely suppresses graphitization and leads to the formation of cementite or carbides (Pluphrach, 2010).

Davis (1996) reported that alloying elements can be added in common cast iron to enhance some mechanical properties. They influence both the graphitization potential and the structure and properties of the matrix.Al, C, Si and Ti increase the graphitization potential during the eutectic transformation while Ni and Cu decrease it during the eutectoid transformation, thus raising the pearlite-ferrite ratio. Increasing the amount of pearlite raises the strength and hardness of the cast iron.

Grey cast iron has become a popular cast metal material which is widely applied in modern industrial manufacturing because of its good castability, wear resistance, machinability, high damping capacity, and low cost. Industrial castings practice can influence nucleation and growth of graphite flakes, so that type and size increase the desired properties. Thus,it is important to control the flake graphite morphology that has a direct influence on the properties of grey cast iron (Pluphrach, 2010).

For the purpose of developing improved materials for applications in various industries, the present research work investigated the effects of copperadditions and section thickness on some mechanical properties and the morphology of graphite flakes in greyiron castings.Copper is preferred because it improves to a large extent, the fluidity of the metal (Mikhailov, 1990).

1.2 Statement of the Problem

The solidification rate of molten grey cast iron is the most important factor controlling the size and length of the graphite flakes which in turn determines the strength of the grey cast iron. A higher solidification rate gives shorter flakes and higher strength; slow cooling on the other hand produces longer flakes making the iron to have poor mechanical properties. The second factor is the carbon content. Higher carbon content gives more carbon in the structure resulting in longer flakes (Global Casting Magazine, 2013).

The most obvious things to do to improve grey iron strength are increasing the solidification rate or reducing the carbon equivalent. Both of these methods have disadvantages;a lower carbon equivalent will reduce castability and increase the probability of shrinkage defects, also increased solidification rate means increased risk for carbide formation. Hence, it is necessary to look for other ways of refining the

graphite morphology of grey iron castings without reducing the carbon equivalent and losing the good machinability of the greycast iron.

Grey cast iron has good mechanical and thermal properties; very good castability which as a result gives a material that is traditionally suitable for the production of automotive castings (engine block and brake components). However, due to weight requirements, grey iron has been challenged by aluminium and compacted graphite iron, which are more expensive and energy consuming to produce. To comply with these challenges, grey iron foundries must produce grey iron grades with better mechanical properties compared to the traditional grades for engine cylinder blocks (Global Casting Magazine, 2013).

Based on the aforementioned reasons, this research has focused on alloying grey cast iron with copper in order to enhance its graphite morphology and improve its mechanical properties.

1.3Justification/Significance of the Study

In October 2013, the Nigerian Government announced an Automotive Industry Development Plan, which seeks to expand domestic vehicle manufacturing (NTE Report, 2014). As a result, Small, Medium and Micro-Enterprises (SME) are being established to produce automotive parts and components locally in order to reduce the Country's dependence on imported parts. Therefore, concerted efforts should be made in researching on how these parts and components can be produced with optimum standardization at a reasonable cost.

The enhancementof the matrix structure and mechanical properties of greyiron castings are expected to bring several benefits in casting industries as the constituted element (copper) reduces chilling tendency in thin sections. This versatility leadsto expansion in

the engineering applications of as-cast grey iron, thus producing parts and products with longer lifespan and superiority in terms of performance.

The outcome of results in this research project will allow the designers working for the automotive industry to make a better informed choice between competing materials (steel and aluminium alloys) and greycast iron, thus decreasing the overall cost of the automobile.

1.4Aim and Objectives of the Study

This work is aimed at investigating the effects of copper additions and section thickness on some mechanical properties and the morphology of graphite flakes in grey cast iron.

Specific objectivesare;

i. To cast unalloyed and copper alloyed grey cast iron with varying section thickness of 10 mm, 25 mm and 75 mm.
ii. To examine the influence of copper additions on the type of graphite flakes formed in the microstructure of grey cast iron.
iii. To determine the average length of graphite flakes using SEM as related to the percentage composition of copper.
iv. To determine the effect of section thickness on graphite flakes formation and the mechanical properties of the produced greycast iron.

1.5 Scope of the Study

One heat of unalloyed grey cast iron and three heats of grey cast iron alloyed with different compositions of copper (0.55%, 0.70%, and 1.15%) were produced and poured in a mould with varying section thickness of 10 mm, 25 mm and 75 mm respectively.

The microstructures of each section thickness of the produced unalloyed and copper alloyed grey cast iron were examined using an optical metallurgical microscope.

The average length of graphite flakes of all the samples was measured using a scanning electron microscope.

The tensile strength, impact strength and hardness properties of all the samples of grey cast iron were determined using Honsfieldtensometer, Charpy impact machine and Rockwell hardness tester respectively.

CHAPTER TWO

LITERATURE REVIEW

2.1Cast Iron

Based on the iron- iron carbide phase diagram (Figure 2.1), ferrous metals are classified as steels or cast irons. Plain iron carbon alloys with carbon up to 2.11% in iron are called steels and higher than this value, the alloys are called cast irons. Theoretically, the carbon content of cast iron lies between 2.11% and 6.67%; in practice, however, most cast irons contain between 3.0% and 4.5% C and, in addition, other alloying elements (Callister, 2007).

A re-examination of the iron– iron carbide phase diagram (Figure 2.1) reveals that alloys within this composition range (3.0% to 4.5%) becomecompletely liquid at temperatures between approximately 1150ºC and 1300ºC (2100ºF and 2350ºF), which is considerably lower than for steels. Thus, they are easilymelted and amenable to casting. Furthermore, some cast irons are very brittle,and casting is the most convenient fabrication technique (Callister, 2007).

The best method of classifying cast iron is according to metallographic structure. There are four variables to be considered which lead to the different types of cast irons, namely the carbon content, the alloy and impurity content, the cooling rate during and after freezing, and the heat treatment after casting. These variables control the condition of the carbon and its physical form. The carbon may be combined as iron carbide in cementite, or it may exist as free carbon in graphite. The shape and distribution of the free carbon particles will greatly influence the physical properties of the cast iron (Chakrabarti, 2005).

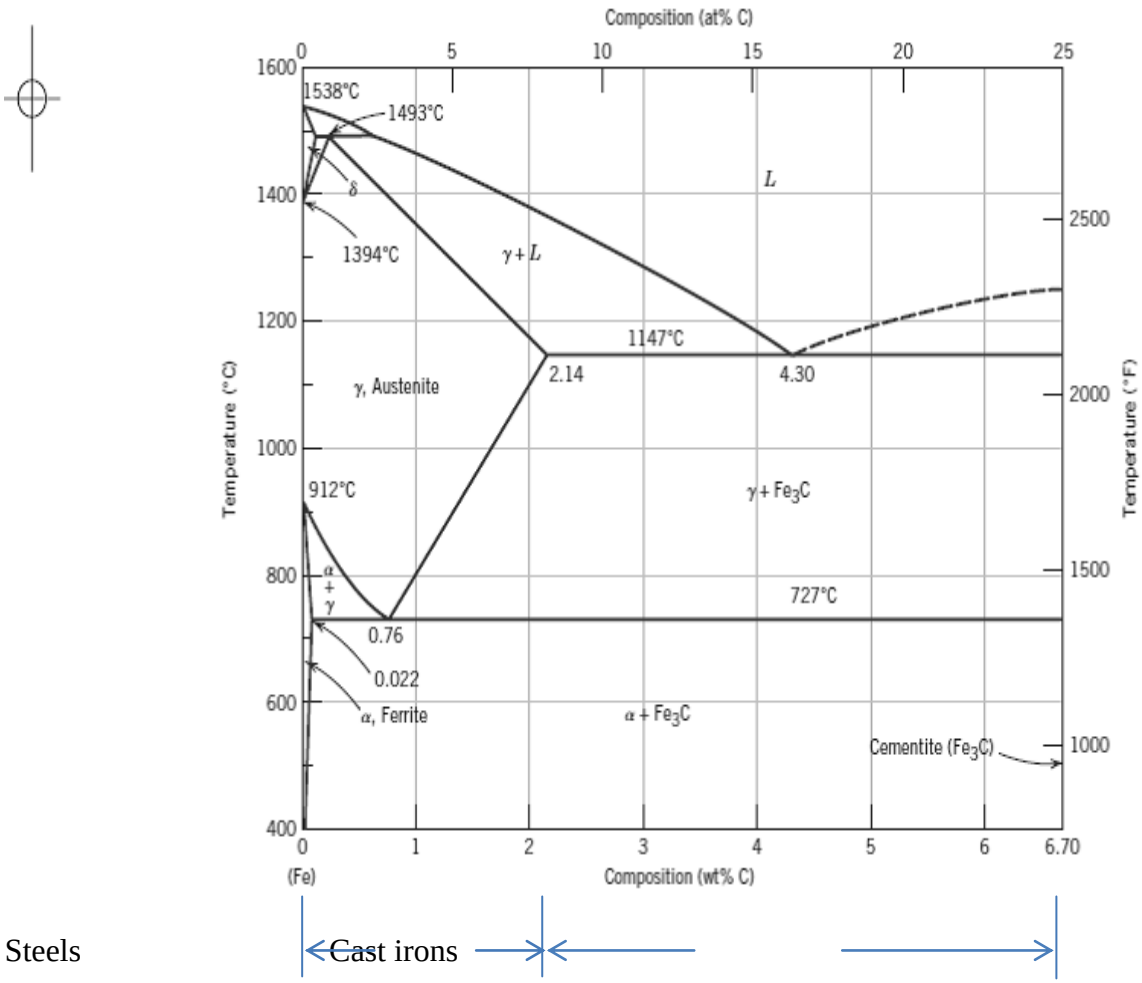


Figure 2.1.: Iron- Iron Carbide Phase Diagram (Callister, 2007).

2.2 Classes of Cast Iron

Depending on the shape and form of the carbon in the cast iron and alloying additions, cast iron is usually classified as white cast iron, malleable cast iron, grey cast iron, ductile cast iron and alloy cast iron.

2.2.1 White cast iron

White cast iron derives its name from the fact that it's freshly broken surface shows a bright white fracture. White cast iron has almost all its carbon chemically combined in form of cementite, which is a very hard and brittle constituent (Khanna, 2002). The properties of white cast iron include: high hardness, excellent abrasive wear resistance,

high strength in compression and very brittle. White cast iron is the first step in the production of malleable iron castings. Other uses include: crusher jaws and hammers, crusher balls, liners for ball mills, rolls for crushing ores and rolling mills (Ause, 2008).

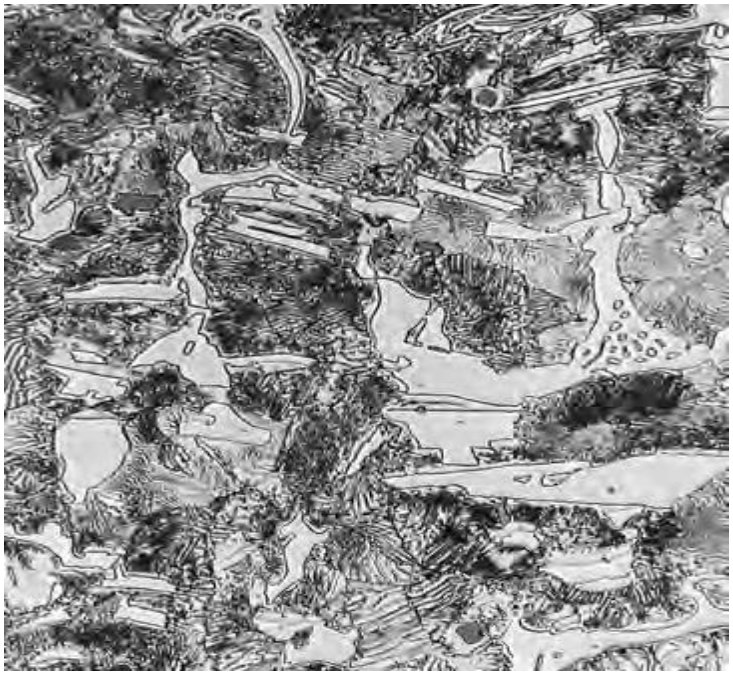


Figure 2.2: White iron: the light cementite regions are surrounded by pearlite, which has the ferrite–cementite layered structure (Callister, 2007).

2.2.2 Malleable cast iron

Malleable cast irons are similar structurally to grey and nodular cast irons because they can have ferrite or pearlitic matrix, the only difference is that malleable cast iron is obtained from the hard and brittle white iron through controlled malleabilizing heat treatment. The properties of malleable cast iron include: high toughness/ductility, good machinability, strong in tension and compression, good wear resistance and vibration damping capacity. Areas of applications include: for tough farm implements for example ploughs, tractor rakes and harrows, automobile parts such as gears, brake drums, cams and so forth (Millis, 1972).

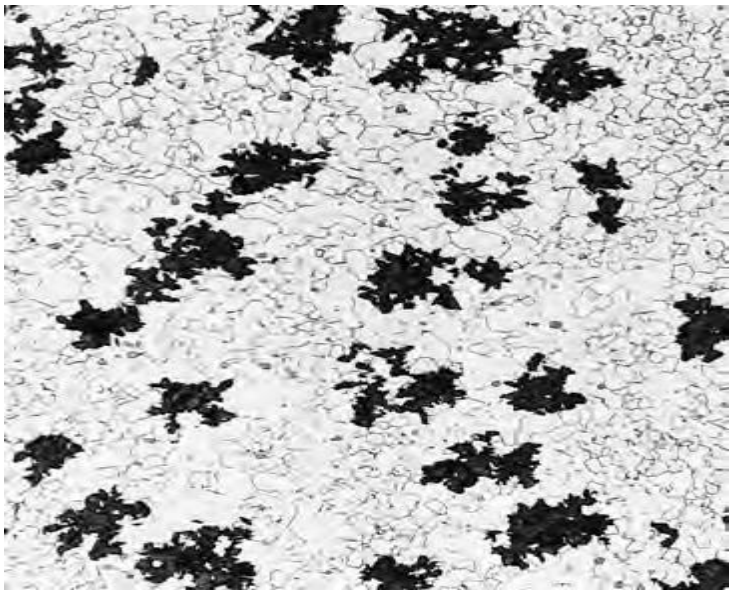


Figure 2.3.:Microstructure of Malleable cast iron: dark graphite rosettes (temper carbon) in an α–ferrite matrix(Callister, 2007).

2.2.3 Alloy cast iron

Alloy cast iron is a general group where we add sufficient amount of element or elements to produce a measurable modification in the physical or mechanical properties. By doing so we can achieve an improvement in properties like resistance to corrosion, resistance to heat or wear or to improve mechanical properties like fatigue strength, tensile strength (Ambooken, 2006).

2.2.4 Ductile cast iron

It is a cast iron in which the graphite is present as tiny balls or spheroids in ductile metallic matrix. Microstructure is more similar to the grey cast iron, consists of graphite nodules in pearlitic-ferritic matrix. The nodules are formed by addition of "nodulizers" like Magnesium, Yttrium or Cerium into the melt (Dommarco*et al*., 2006).

It has high elevated temperature properties, corrosion resistance, and wear resistance. Its applications are in automobile construction, industrial machinery, wind turbine

electrical energy generation, valves, air conditioning machinery, lawn & garden equipment, agricultural products and many other types of castings (Ambooken, 2006).

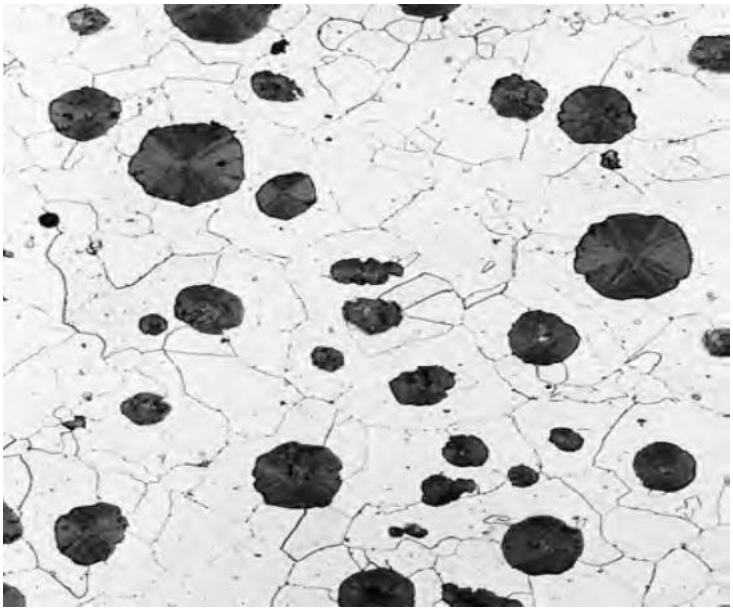


Figure 2.4: Nodular (ductile) iron: the dark graphite nodules are surrounded by an α-ferrite matrix (Callister, 2007).

2.2.5Grey cast iron

Grey cast iron is the most common type of all cast irons with carbon content between 3-3.5%. The microstructure contains pearlitic matrix, with flakes of graphite in it (De Campos*et al.,* 2005). Carbon comes out of solution as graphite due to the presence of silicon during cooling. Grey cast iron has good mechanical properties like good corrosion resistance, high thermal conductivity, improved wear resistance and high machinability (Callister, 2007).

According to Allen (1969), the matrix structure of grey cast iron can be readily changed by heat treatment but the flakes once formed, cannot be changed by heat treatment. However, the quantity, shape and size of the graphite flakes may vary within a wide range. Based on the type of matrix, this iron could be grouped structurally into;

i) Ferriticgrey cast iron

ii) Pearliticgrey cast iron

iii) Ferritic – pearliticgrey cast iron

iv) Pearlitic – ferriticgrey cast iron (Allen, 1969; Smith, 1981).

Major applications of grey cast iron are in making such products as, engine blocks, electric-motors, pipes, machine bases and cook wares (Ambooken, 2006).

Figure 2.5.:Grey iron: the dark graphite flakes are embedded in anα-ferrite matrix (Callister, 2007).

The composition of grey iron must be selected in such a way as to satisfy three basic structural requirements:

1. The required graphite shape and distribution
2. The carbide-free (chill-free) structure
3. The required matrix

For common cast iron, the main elements of the chemical composition are carbon and silicon. High carbon and silicon contents increasethe amount of graphite or Fe_3C, that is the graphitization potential of the iron as well as its castability thereby decreasing chilling tendency. This is due to ferrite promotion and the coarsening of pearlite.

The manganese content however, varies as a function of the desired matrix. Typically, it can be as low as 0.1% for ferritic irons and as high as 1.2% for pearlitic irons, because manganese is a strongpearlite promoter (Davis, 1996).

From the minor elements, phosphorus and sulphur are the most common and are always present in the composition. They can be as high as 0.15% for low-quality iron and are considerably less for high-quality iron, such as ductile iron orcompacted graphite iron. The effect of sulphur must be balanced by the effect of manganese. Without manganese in the iron, undesired iron sulphide (FeS) will form at grain boundaries. If the sulphur content is balanced by manganese, manganese sulphide (MnS) will form, but this is harmless because it is distributed within the grains.

Other minor elements, such as aluminium, antimony, arsenic, bismuth, lead, magnesium, cerium, and calcium, can significantly alter both the graphite morphology and the microstructure of the matrix (Davis, 1996).

2.3 Types of Graphite Flakes in GreyCast Iron

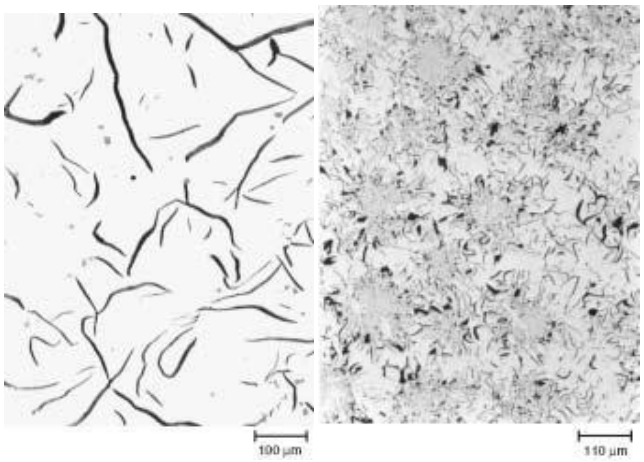
The typical graphite shapes for flake graphite according to ASTM A 247 are described below.

Type A graphite is found in inoculated irons cooled at moderate rates. In general, it is associated with the best mechanical properties, and cast irons with this type of graphite exhibit moderate undercooling during solidification.

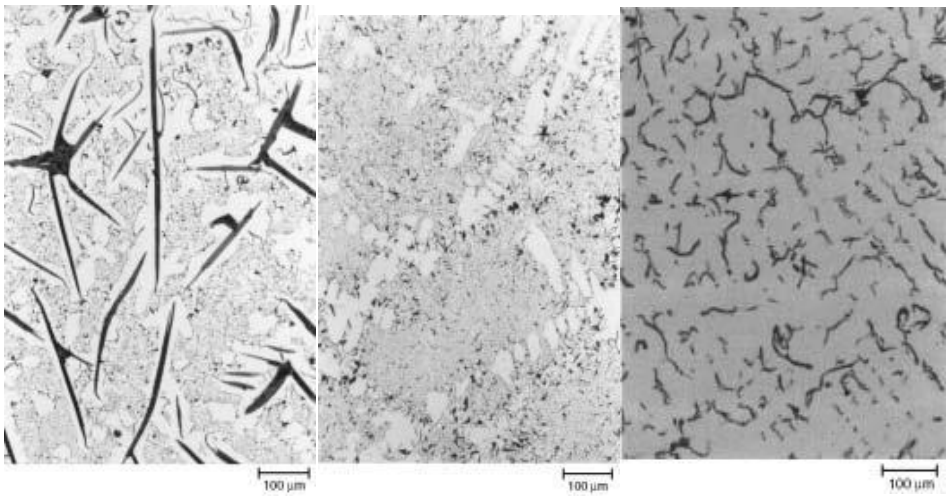
Type B graphite is found in irons of near-eutectic composition, solidifying on a limited number of nuclei. Large eutectic cell size and low undercooling are common in cast irons exhibiting this type of graphite.

Type C graphite occurs in hypereutectic irons as a result of solidification with minimum undercooling.

Type D graphite is found in hypoeutectic or eutectic irons solidified at rather high cooling rates, while type E graphite is characterised for strongly hypoeutectic irons.



(a) (b)



(c) (d) (e)

Figure 2.6.: Flake graphite (a) Type A (b) Type B (c) Type C (d) Type D and (e) Type E (Source: ASM Handbook, 2004).

2.4Effect of Alloying Elements

Alloying elements can be added in common cast iron to enhance some mechanical properties. They influence both the graphitization potential and the structure and properties of the matrix. In general, alloying elements can be classified into three categories:

I. Silicon and aluminium increase the graphitization potential for both the eutectic and eutectoidtransformations and increase the number of graphite particles. The addition of silicon reduces the solubility of carbon in the iron and also decreases

the carbon content of the eutectic and the pearlite phase. It also raises the transformation temperature of ferrite plus pearlite to austenite (Krause, 1969).

II. Nickel, copper and tin increase the graphitization potential during the eutectic transformation but decrease it during the eutectoid transformation. They strengthen the matrix and decrease the tendency to form hard edges on castings. Since they are mild graphitizers, they are often substituted for some of the silicon in grey cast iron (Krause, 1969).

III. Chromium, molybdenum, tungsten and vanadium decrease the graphitization potential at both stages. Thus, they increase the amount of carbides and pearlite. As long as carbide formation does not occur, these elements increase strength and hardness. Above a certainlevel, any of these elements will determine the solidification of a structure with Fe_3C (mottled structure), which will have lower strength but higher hardness (Davis, 1996).

2.4.1 Copper in grey cast iron

Copper is reported to have a multitude of effects when added to grey cast iron. It increases graphitization, promotes, refines and stabilizes pearlite. It is this effect on pearlite, along with its solid solution strengthening of ferrite, which allows for the increase in strength and hardness (Global Casting Magazine, 2013).

2.5 Cooling Rate

The cooling rate, like the chemical composition, can significantly influence the as-cast structure and therefore the mechanical properties of the grey cast iron. The cooling rate of a casting is primarily a function of its section size (Davis, 1996).

Increasing the cooling rate will:

I. Refine both graphite size and matrix structure; this will result in increased strength and hardness.

II. Increase the chilling tendency; this may resultin higher hardness, but will decrease thestrength.

Consequently, composition must be tailored in such a way as to provide the correct graphitization potential for a given cooling rate. For a given chemical composition and as the section thickness increases, the graphite becomes coarser, and the pearlite/ferrite ratio decreases, which results in lower strength and hardness (Davis, 1996).

2.6 Production of Grey Cast Iron

Grey cast iron can be produced by inoculating low sulphur liquid cast iron with a silicon containing alloy just before or during casting (Global Casting Magazine, 2013).

2.6.1 Raw materials

To produce grey cast iron with the best combination of strength and toughness, raw materials must be chosen which have lower than 0.02% sulphur and are low in trace elements. Higher strength grades of greyiron can also be made with common grades of constructional steel scrap, pig iron and foundry returns, but certain trace elements e.g. lead and antimony are usually kept as low as possible to achieve good graphite structure (Ashraf, 2008).

2.6.2 Inoculation

The liquid treatment of cast iron is of paramount importance in the processing of this alloy because it can dramatically change the nucleation and growth conditions during solidification. As a result, graphite morphology, and therefore properties, can be significantly affected. In grey iron practice, the liquid treatment used, termed inoculation, consists of minute additions of minor elements before pouring. Typically, ferrosilicon with additions of aluminium and calcium, or proprietary alloys, is used as inoculants (Davis, 1996). The main effects of inoculation are:

I. An increased graphitization potential because of decreased undercooling during solidification; as a result of this, the chilling tendency is diminished, and graphite shape changes from type D or E to type A.

II. A finer structure (i.e., higher number of eutectic cells) with a subsequent increase in strength.

III. Reductionof non-uniform properties within a casting of varying section sizes. Thinner sections solidify at a faster rate than thicker sections. As a result, properties such as tensile strength of these sections will be different. Inoculation provides more uniform properties within the casting by reducing the solidification rate in thinner sections.

IV. Improving the tensile strength, impact strength, toughness, wear resistance and machinability of the casting.

2.6.2.1*Inoculants*

Almost every material inoculates to some degree. For effective and well controlled inoculation, ferro-silicon of controlled chemical composition is usually used. Active inoculating elements are: Ca, Al, Ba, and some others (Ashraf, 2008).

The inoculant should be stored in closed containers because its effectiveness deteriorates with time when exposed to open air (Ashraf, 2008).

2.6.2.2*Methods of inoculation*

Cast iron may be inoculated by several methods,amongst which include:

Ladle inoculation: Iron is inoculated by adding inoculant to the liquid metal as it is transferred from the furnace to the pouring ladle. The turbulence quickly dissolves the inoculant and evenly disperses it throughout the molten bath (Ashraf, 2008).

In-stream inoculation: In many automatic pouring operations, inoculation is done in-the-stream.

In-mould inoculation: Inoculants may also be added as a preformed insert placed in the pouring basin of a mould or as granulated inoculant placed in the gating system.

In-stream and in-the-mould inoculation techniques offer little inoculation fade, and generally require less inoculant material to provide the desired results (Ashraf, 2008).

2.7Brief Review of Previous Research Works

Many attempts were made to understand and predict the behaviours of greycastiron that includes the study of graphite morphology and solidification behaviour, the response of matrix structure to heat treatment, the correlation between the structure and mechanical properties, the methods of inoculation and possible areas of application. A brief review of some of the published research works addressing these issues is presented below;

Pluphrach, (2010) studied the effect of solidification on graphite flakes microstructure and mechanical properties of an ASTM A-48 grey cast iron using SKD 11 tool steel, S45C medium carbon steel andSS400 hot-rolled steel molds. He concluded that the mechanical properties of structural ASTM A-48 grey cast iron materials strongly depend on their microstructure; reduced graphite content increases the tensile strength.

Uchimoto*et al*., (2010) investigated the feasibility of characterizing the shape and size of graphite in flake graphite cast iron based on electromagnetic non-destructive methods.Several flaky graphite cast iron specimens containing graphite of various shapes and sizes were prepared and their electromagnetic properties such as conductivity and relative permeability were evaluated systematically. Both the conductivity and the relative permeability were found to mainly depend on the shape and size of graphite.

Behnam*et al*., (2010)studied the effect of cooling rate on the primary dendrite arm spacing (DAS), secondary dendrite arm spacing (SDAS), thickness of ferrite–cementite layer (λ_e) and the hardness (HB) of grey cast iron. Results showed that both DAS and

SDAS and also λ_e were highly dependent on the cooling rate, and they decrease as the cooling rate increases. More attempts were also made to correlate the hardness value with DAS, SDAS and λ_e. It was found that hardness increases as DAS, SDAS and λ_e decrease.

Moonesan*et al*., (2012) investigated the effect of some alloying elements on the thermal shock resistance of low alloyed grey cast iron. The results showed that the thermal shock resistance of the grey cast iron, containing 0.8% Mo, 0.2% Cr and 0.08% Sn as alloying elements was enormously increased in comparison with unalloyed grey cast irons.

Adedayo, (2013) investigated the characteristic effects of graphite flake sizes on some mechanical properties of grey cast iron. Six mould materials with heat storage capacities ranging from 1.52 $kJ.m^{-2}.K^{-1}.s^{-1/2}$ to 2.16 $kJ.m^{-2}.K^{-1}.s^{-1/2}$ were prepared and used to cast some grey cast iron samples whose microstructures were observed by optical microscopy. Mechanical properties of the grey iron were evaluated. The results showed that the properties increased with the heat storage capacity of the mould. Also, the microstructures showed a dependence on heat storage capacity of the mould.

Sahu *et al.,* (2014)examined the effect of section thickness on microstructure of grey cast iron. Grey cast iron micro-structure consists of flakes of graphite with a matrix of pearlite or ferrite. It was found in this study that size of the graphite flake changes with the change in cooling rate. Flake size affects properties like hardness, UTS and damping capacity of grey iron. It was observed that small section thickness contains small graphite flakes, whereas thick sections consist of larger graphite flakes. Hardness of thin section was also found greater than that of thick section.

Agunsoye *et al*., (2014) investigated the effect of copper addition on the mechanical and wear properties of grey cast iron. The results revealed that the presence of copper in the

melt of grey cast iron inhibited the formation of cementite. The impact energy of the grey cast iron increased with percentage weight of copper addition making the developed Fe-Cu alloy an excellent material which can be used in the vibration damping application especially in shock absorber.

In summary, it can be seen from the reviewed studies and researches, that the role an alloying element such as copper plays in the modification of the graphite flake morphology and its subsequent effect on the mechanical properties of grey cast iron has not been established fully. There is also little or no existing literature on the optimum composition of copper that is required to increase the strength and hardness of grey cast iron.The present study was carried out in order to address the aforementioned research gaps.

CHAPTER THREE

MATERIALS AND METHODS

3.1 Raw Materials

Low carbon steel scraps, graphite electrode, ferro-silicon alloy and copper wires sourced from the market were used to produce different classes of grey cast iron using a commercial electro-induction foundry furnace at L & CU International Foundry Limited, Kaduna. The chemical composition of the low carbon steel is shown in Table 3.1.

Silica sand and water were used to produce standard step sand mould with varying thicknesses of 10mm, 25mm and 75mm. Other materials include: polishing powder, water, grinding papers, polishing cloth, cotton wool, nitric acid and ethanol.

Table 3.1: Chemical composition of low carbon steel

Element	**C**	**Mn**	**Si**	**P**	**S**	**Mo**	**Fe**
Content%	0.20	0.40	0.15	0.035	0.040	0.02	99.15

3.2 Equipment

The equipment used for this experiment includes;

Lathe machine (AFM, type: TUE 40, Model 9063),milling machine (Victoria – BEC-108767 110), electric induction furnace, polishing machine (POLIMET polisher S/N: 281-GGG-V-897), Hounsfield Tensometer (S/N: W4729), optical microscope (model no: NJF-120A),Indentec Universal Rockwell Hardness Tester (model 8187LKV), impact testing machine, scanning electron microscope (Phenom Pro X model) and an optical emission spectrometer (Shimadzu OES model PTD7000).

3.3 Methods

The following steps as outlined below were followed during the experimental process.

3.3.1 Moulding method

Four sand moulds were prepared from a mixture of dried fresh silica sand, bentonite and water using the wooden pattern made with varying section thicknesses of 10mm, 25mm and 75mm(Figure 3.1). The moulds were labelled A, B, C, and D.

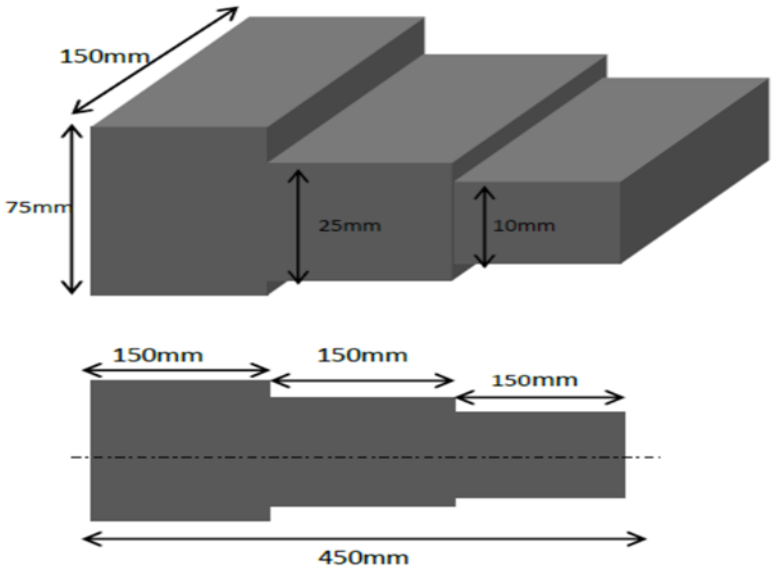


Figure 3.1: Experimental casting patterns with varying section thicknesses (Mikhailov, 1990).

3.3.2 Production of grey iron with and without copper alloy

The charge consisting of low carbon steel scraps and graphite electrode was melted in a 600kg commercial electro-induction foundry furnace. The molten metal was tapped at a temperature of 1300ºC into a 60kg ladle. The inoculant (ferro-silicon) was then added directly in the stream while pouring the melt into the ladle to ensure proper mixing.

The formula in equation 3.1 was used to determine the amount of alloying element to be added in line with the work done by Ziółkowskia and Wrona(2007), and Soiński and Góraj(2009).

$$(Y)=\frac{[A-B]\ x\ [Q]}{W} \qquad 3.1$$

Y = amount of alloying element to be added

A = required amount

B = amount in base metal

Q = total weight of the charge

W = purity of the alloying element

The first batch of the melt that corresponds to grey cast iron without the addition of copper (control sample) was poured into the step sand mould with varying section thicknesses of 10mm, 25mm and 75mm labelled A. Then 0.5% copper was added to the molten grey cast iron in the ladle and thoroughly stirred with steel rod. The alloy mixture was then poured into the step sand mould labelled B. This procedure was repeated twice in order to produce the copper alloyed grey cast iron varied at 0.8% Cu and 1.1% Cu labelled C and D respectively.

All the melts were allowed to cool to room temperature while in the mould, after which the castings were removed and prepared for machining. The chemical analysis of the grey cast iron produced with and without the addition of copper as obtained by using the optical emission spectrometer (OES) is presented in Table 3.2.

Table 3.2:Chemical composition of unalloyed and copper alloyed grey cast iron

Elements	**Heat 1 %**	**Heat 2 %**	**Heat 3 %**	**Heat 4 %**
C	3.69	3.83	3.88	3.56
Si	1.06	1.46	1.37	1.53
Mn	0.20	0.22	0.22	0.22
P	0.04	0.03	0.04	0.03
S	0.02	0.02	0.02	0.02
Cr	0.08	0.07	0.08	0.07
Cu	0.02	**0.55**	**0.70**	**1.15**
Ti	0.01	0.01	0.01	0.01
Co	0.01	0.01	0.01	0.02
V	0.01	0.01	0.02	0.01
Fe	94.86	93.79	93.65	93.38
C.E	4.06%	4.33%	4.35%	4.08%

The carbon equivalent (C.E) was calculated using the relationship in equation 3.2 to determine how close the grey cast irons are to the eutectic composition of 4.3%.

C.E= %C + 1/3 %(Si+ P) 3.2

Heat 1 and Heat 4 having C.E of 4.06% and 4.08% respectively are hypoeutectic grey cast iron alloys. Whereas, Heat 2 and Heat 3 having C.E of 4.33% and 4.35% arehypereutectic alloys or near eutectic grey cast iron.

3.3.3 Machining of test samples

Prepared samples from each section thickness (10mm, 25mm and 75mm) of the unalloyed and copper alloyed grey cast iron were cut and machined to standard impacttest samples, tensile test samples and hardness/microstructural analysis samples.

3.3.4 Microstructural examinations

3.3.4.1 *Optical microscope*

Specimens (unalloyed and copper alloyed) from each of the section thickness were prepared for optical microscopic examination. The specimens were ground on a water lubricated silicon carbide abrasive papers of 180, 240, 320, 400 and 600 grit sizes. Polishing was carried out on 15cm rotating discs of a POLIMET universal polishing machine with synthetic velvet polishing clothes impregnated with 1 µm Alumina paste. The specimens were then etched with 2% Nital solution using the swabbing method with cotton wool soaked in the etchant and then rinsed with water.

The microscopic examination was carried out using a Metallurgical photographic microscope (model number NJF-120A) to obtain the different microstructures of the grey cast iron.

3.3.4.2*Scanning electron microscope*

In order to measure the graphite flake length and thickness, the surface of all the specimens (unalloyed and copper alloyed) to be examined were polished and then

etched (as described above). APhenom Pro X model scanning electron microscope with an accelerating voltage of 10kV and BSD full mapping was used to analyse and calculate the graphite flake length of each specimen.Thirty (30) different flakes were measured in each specimen and the average length was recorded. An average of the longest flakes was recorded as the maximum flake length while an average of the shortest flakes was recorded as the minimum flake length in all the grey cast iron specimens. Figure 3.2 shows a snapshot of how the measurement was carried out. The graphite morphology was rated for the graphite size class and graphite type in accordance with the ASTM A247standard.

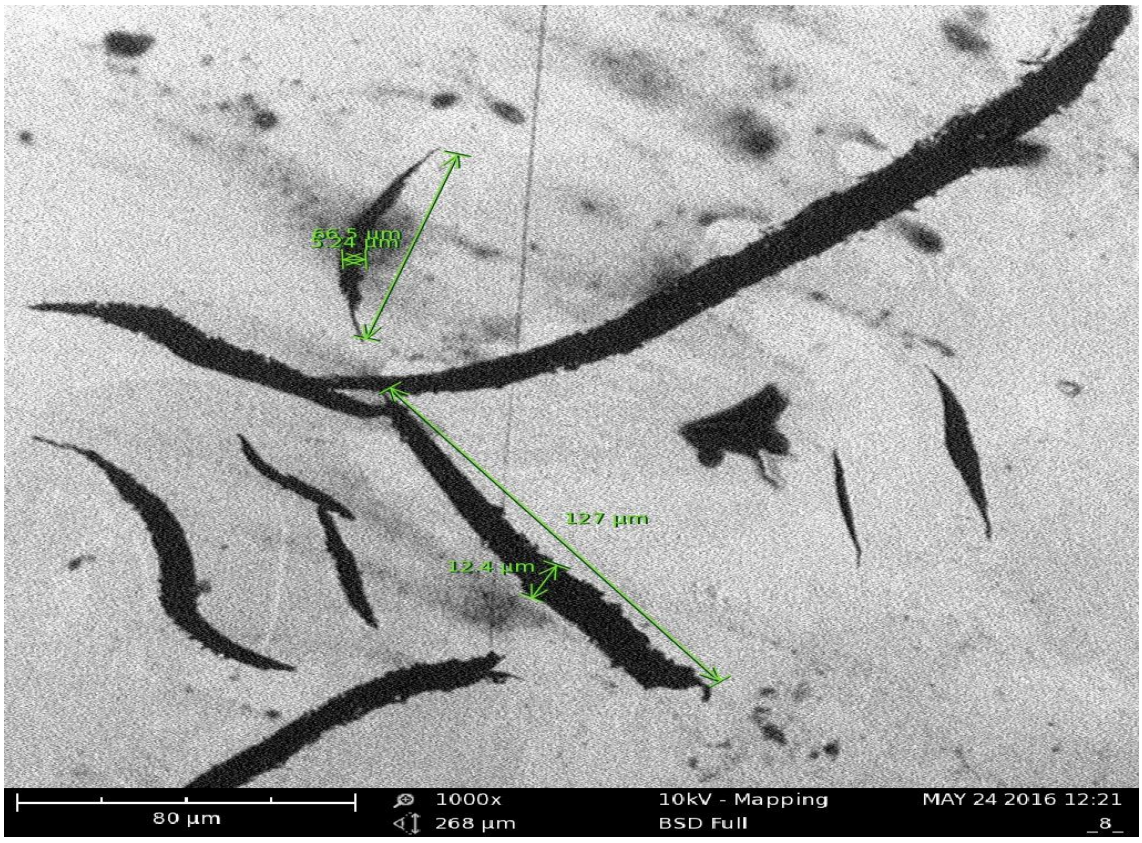


Figure 3.2.: SEM micrograph showing the measured graphite flake length of the grey cast iron.

3.3.5 Mechanical tests

3.3.5.1 *Tensile test*

The tensile test samples were machined to standard dimensions as specified in ASTM A370(Figure 3.3). The test method adopted was ASTM E8. The test sample was mounted at its ends onto the holding grips of the testing apparatus.Each sample was subjected to tension till fracture, after which tensile strength and percentage elongation weretaken.

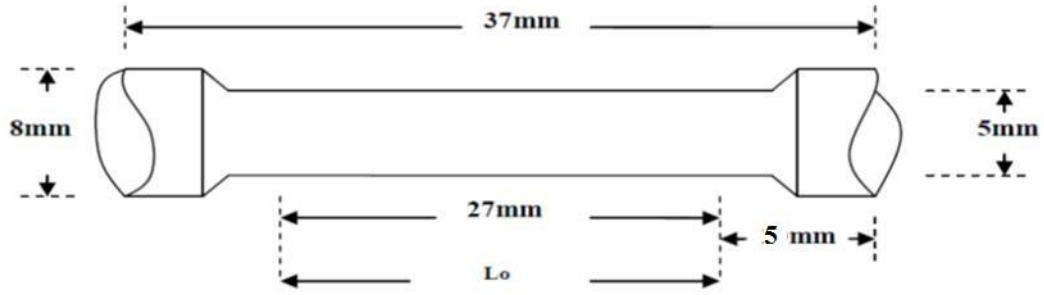


Figure 3.3: Standard tensile test specimen
(Source: ASTM, 2007a).

3.3.5.2 *Hardness test*

Indentec Universal Rockwell hardness tester model 8187LKV was used. The specimen was placed on the anvil and moved up until it came in contact with the Diamond cone (120º) indenter, then the minor load of 10kgf was applied while setting the dial gauge to zero. The major load of 150kgf was then applied on the specimen and the corresponding hardness value was recorded on the C-scale.

The procedure was repeated at 4 different points on the test piece and the average was recorded.

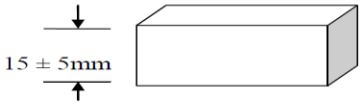


Figure 3.4: Standard hardness test piece.
(*Source:* ASTM, 2007a)

3.3.5.3 *Impact test*

The impact test samples were machined to standard dimensionsof 10 mm X 10 mm X 55 mm with a 1 mm deep V-notch at 45º (Figure 3.5) as specified in ASTM A370. The test specimen was gripped horizontally in a vice, then the trigger was released and the registering pointer of the quadrant scale indicated the energy absorbed in Joules to break the specimen. The energy absorbed in breaking the sample was recorded and the same was repeated for all the test pieces.

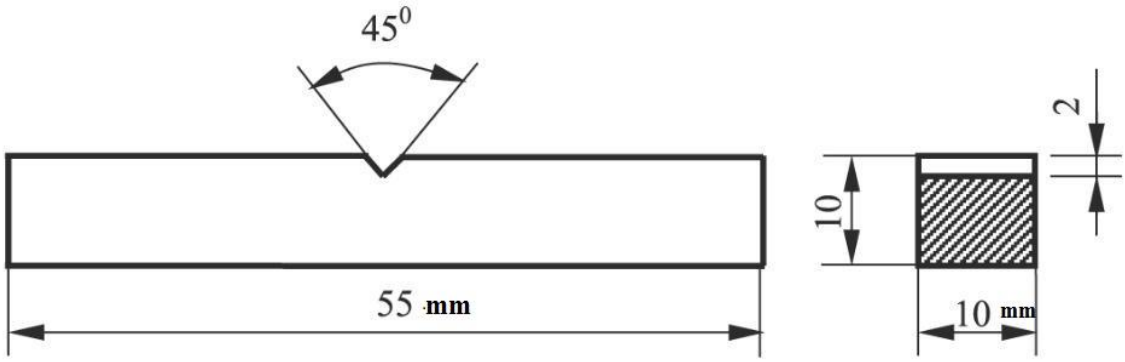


Figure 3.5: Impact test specimen.
(Source: ASTM, 2007a)

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Introduction

This chapter presents the SEM micrographs and the mechanical properties tests resultsof the produced unalloyed and copper alloyed grey cast iron with varying section thicknesses; alongside with the discussion of such results. Different variables have been studied during the present research. The first variable was the effect of copper additions on the graphite morphology and mechanical properties of the grey cast iron. The second variable was the effect of section thickness on the graphite morphology and mechanical properties of the grey cast iron.

Figure 4.1.: The as-cast unalloyed and copper alloyed grey cast iron ingots. (a) Shows the four different classes labelled A, B, C and D. (b) shows the casting with the varying section thickness.

Figure 4.1 shows the as-cast unalloyed (labelled A) and copper alloyed grey cast iron (labelled B, C and D) castings with varied section thickness of 10mm, 25mm and 75mm. It was observed that the castings are in good condition. As stated in chapter 3,

representative samples from each section were cut and machined to standard test specimens.

4.2 Graphite Flake Length

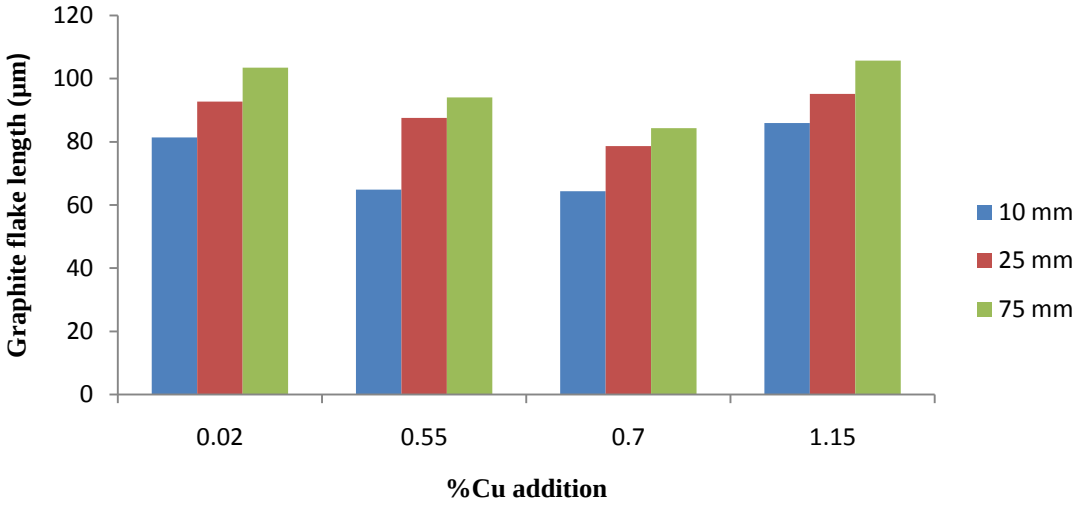


Figure 4.2.: Variation of graphite flake length with percentage addition of copper in the grey cast iron with varying section thickness.

The effect of copper content on the length of graphite flakes in the grey cast iron with varying section thickness is shown in Figure 4.2. In the specimens without copper addition; the smaller the section thickness, the shorter the graphite flakes due to the fast cooling rate. As the section thickness increases, longer graphite flakes tend to form due to longer solidification time. This is in agreement with the findings of earlier researches carried out byKumar and Kumar, (2013), and Sahu *et al*., (2014). Average graphite flake lengths of 81.35µm, 92.7µm and 103.51µm were determined in the 10mm, 25mm and 75mm sections, respectively.

When 0.55% copper was added to the melt, graphite flake lengths of 64.86µm, 87.57µm and 94.05µm were recorded for the 10mm, 25mm and 75mm sections, respectively. The grey cast iron containing 0.7% copper has graphite flake lengths of 64.32µm, 78.65µm,

and 84.32µm for the 10mm, 25mm and 75 mm section thicknesses, respectively. On further addition of copper to 1.15%, graphite flake lengths recorded for the 10mm, 25mm and 75mm section thicknesses were 85.95µm, 95.14µm and 105.68µm, respectively. The trend suggests that addition of copper up to 0.7% impeded the growth of the graphite flakes as a result of strengthening of the pearlite phase and also because it is below the threshold that is required to affect the graphite morphology significantly. However, when the copper content was increased to 1.15%, the formation of softer ferrite structure is favoured, resulting in the development of longer graphite flakes.

4.3Effect of Copper Additions and Section Thickness on the Mechanical Properties of Grey Cast Iron

Figures 4.3, 4.4, 4.5 and 4.6 show the results obtained from mechanical tests carried out on the different classesof grey cast iron.

4.3.1 Tensile properties

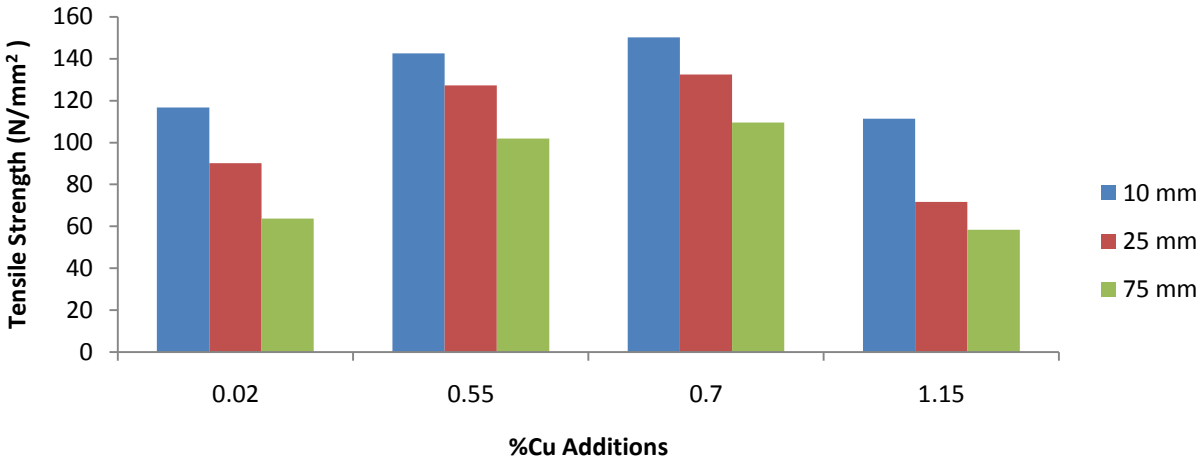


Figure 4.3.: Variation of tensile strength with percentage copper additions in the grey cast iron with varying section thickness.

Figure 4.3 shows the variation of tensile strength with increased copper content in the grey cast iron specimens with 10mm, 25mm and 75mm section thickness. The tensile strengths of the grey cast iron with 10mm section thickness are seen to be much higher

compared to the tensile strengths of the 25mm and 75mm section thickness. The higher strength appears to be associated with the higher cooling rate of the 10mm specimens, which results in smaller and shorter graphite flakes. This agrees with the obtained data in Figure 4.2 and it is in line with Adedayo, (2013).

The Figure also shows a gradual increase in tensile strength with the increase of copper content up to 0.7% and a sharp decline when the copper content was increased to 1.15% in all the grey cast iron specimens. For the 10mm section thickness cast irons; the tensile strength obtained for the unalloyed specimen having 81.35µm graphite flake length is 116.71 N/mm^2. With the copper addition of 0.55% in the greycast iron, the flake length reduced to 64.86µm, thereby increasing the tensile strength to 142.64 N/mm^2. The graphite flake length decreased to 64.32µm and the tensile strength increased to 150.28$N/mm^2$when 0.7% copper was added to the grey cast iron. However,the tensile strength decreased to 111.41 N/mm^2 when 1.15% copper was added to the grey cast iron. This is as a result of the increase in graphite flake length to 85.95µm.This trend could be attributed to the fact that crack propagation through a microstructure of grey cast iron occurs easily due to the increased crack opening at the tip of the graphite flake of increased length and thickness.

The improvement in the tensile strength when 0.55% and 0.7% copper was added is as a result of strengthening of the pearlite phase in the matrix which leads to shorter graphite flake formation.This is similar to the effect of copper on the tensile strength of ductile iron researched by Das *et al*., (2013), and Hsu and Lin, (2014). Both the 25mm and 75mm section thickness specimens exhibitedthe same behaviour.

4.3.2 Percentage elongation

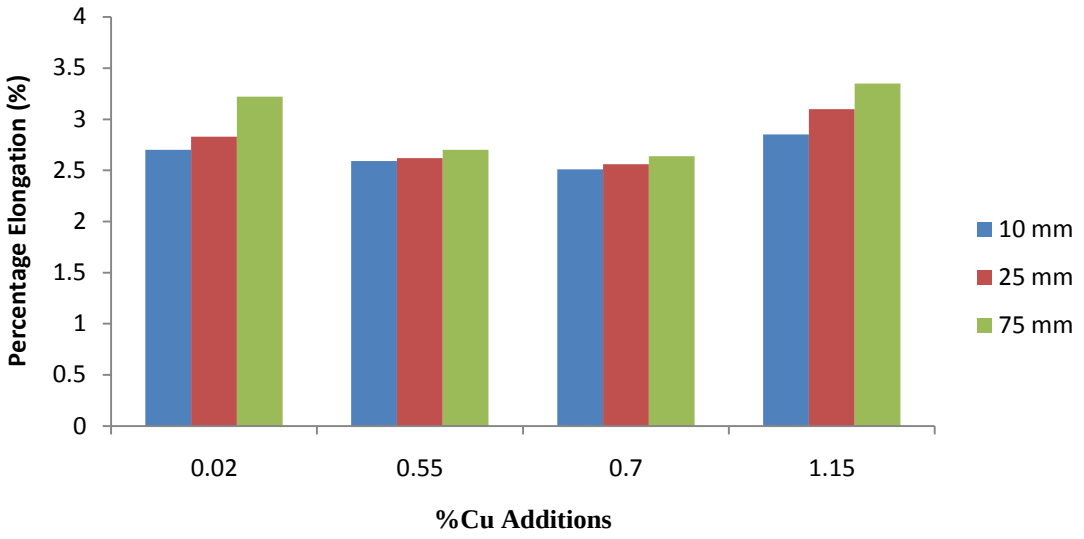


Figure 4.4.: Variation of percentage elongation with percentage copper additions in the grey cast iron with varying section thickness.

Figure 4.4shows the percentage elongation for the unalloyed and copper alloyed grey cast iron with varying section thickness. The results revealed that the elongation increases with increasing section thickness and decreases with the addition of copper up to 0.7% due to the refinement of the pearlite phase by copper.When the copper content was increased to 1.15%, the elongation increased appreciably in all the specimens. This higher ductility is presumably due to an increase in ferrite content and the formation of longer graphite flakes.The present results are similar to the research conducted by Choi *et al*., (2004), who found that the amount of ferrite strongly influences the ductility of ductile iron castings.

The graphite flake length of 105.68µm obtained in the 75mm thick grey cast iron with 1.15% Cu recorded the highest elongation of 3.35% while the least elongation of 2.51% was obtained in the 0.7% Cu alloyed 10mm thick grey cast iron with 64.32µm graphite flake length.

4.3.3 Impact strength

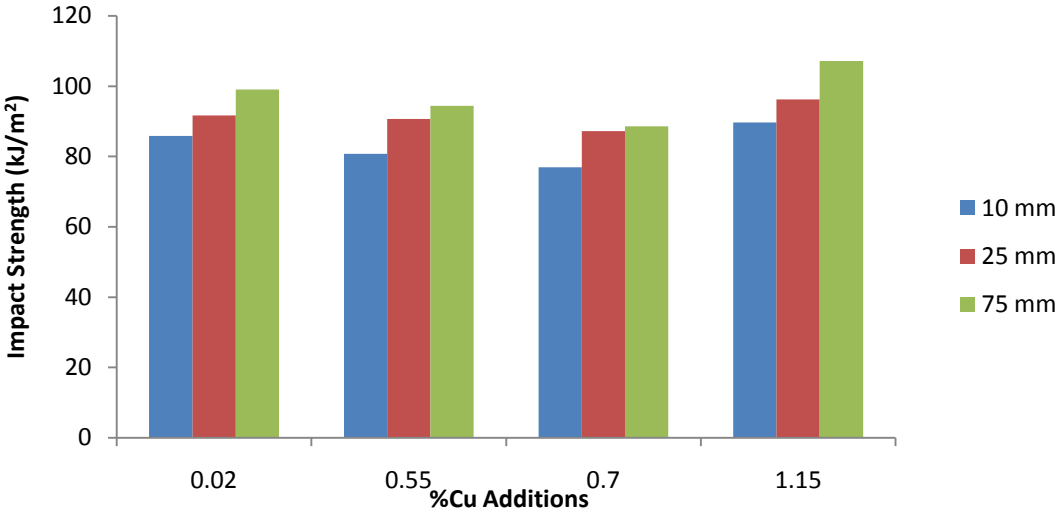


Figure 4.5: Variation of impact strength with percentage copper addition in the grey cast iron with varying section thickness.

Figure 4.5 shows the variation of impact strength with percentage copper addition in the grey cast iron with varying section thickness. The results reveal that the impact strength increases as the section thickness increases. This is attributed to the fact that the average graphite flake length increased from 74.12µm in the 10mm specimensto 88.52µm in the 25mm specimens and to 96.89µm in the 75mm specimens, and also the matrix ductility arising from the pearlite-ferrite ratio in the matrix. The highest impact strength (107.13 kJ/m^2) absorbed before fracture was obtained from the 1.15% Cu alloyed grey cast iron with 75mm section thickness, while the least impact strength of 76.96 kJ/m^{2}was obtained from the 0.7% Cu alloyed grey iron with 10mm section thickness.

It is clear from the trend, that the matrix with long and coarse graphite flakes absorbs more energy than the matrix with fine and short flakes; therefore, it will perform better in vibration damping applications.

The addition of copper up to 0.7% decreases the impact strength in all the specimens, beyond which it starts to increase up to 1.15% addition of copper. In the 10mm specimens, the impact strength decreased from 85.90 kJ/m^2 in the unalloyed grey iron with 81.35µm graphite flake length to 80.79 kJ/m^2 in the 0.55% Cugrey cast iron with

64.86µm graphite flake length. When the copper content was increased to 0.7%, the impact strength and graphite flake length decreased to 76.96 kJ/m^2 and 64.32 µm, respectively. However, with further addition of copper to 1.15%, the impact strength and graphite flake length increased to 89.65 kJ/m^2 and 85.95µm,respectively. The same behaviour was observed in the 25mm and 75mm grey cast iron specimens.

This trend showing the gradual decrease of impact strength as the copper content increases to 0.7% is as a result of higher pearlite content in the structures. This is similar to the effect of copper on the impact strength of ductile iron researched by Hsu and Lin, (2011). However, the enhancement of the impact strength when 1.15% Cu was added is due to higher proportion of the tougher, more ductile and soft ledeburite. This is in line with the work done by Agunsoye *et al*., (2014). In their study, the impact strength of grey cast iron was improved by the addition of copper within 1 - 4% range.

4.3.4 Hardness

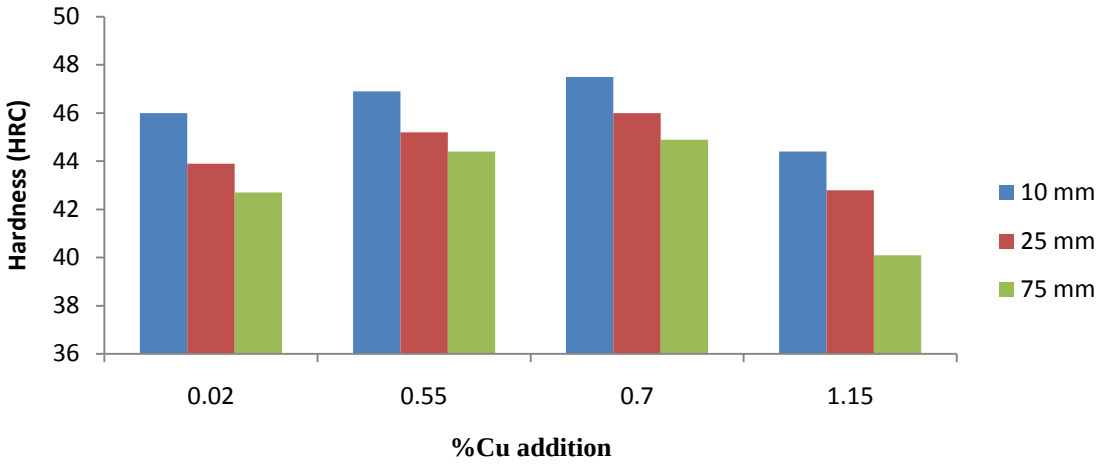


Figure 4.6.: Variation of hardness values with percentage copper addition in the grey cast iron with varying section thickness.

Figure 4.6 shows the variation of hardness with percentage copper addition in the grey cast iron with varying section thickness. The Figure shows that the hardness of the grey

cast iron decreases with increasing section thickness. This could be attributed to the fact that the graphite flake length increases with increasing section thickness which is promoted by the formation of the soft ferrite phase in the matrix. The findings of the present study are supported by the experiments conducted by Kumar and Kumar, (2013) and Sahu *et al*., (2014).

The hardness is observed to increase with the addition of copper up to 0.7% in all the specimens, which is as a result of the development of shorter graphite length, promoted by the strengthening of the pearlite phase by copper in the matrix. This observed trend is similar to the findings of Das *et al*., (2013) about the effect of copper on the hardness of austempered ductile iron (ADI). However, with further addition of copper up to 1.15%, the hardness decreased in all the specimens. At this point, copper influences the formation of more ferrite phases in the matrix which leads to the reduction in hardness.

4.4Effect of Copper Additions and Section Thickness on the Microstructural Properties of Grey Cast Iron.

The micrographs obtained with the aid of scanning electron microscope (SEM) were used to explain the microstructural properties of the grey cast iron specimens instead of the optical micrographs because the SEM micrographs are sharper, clearer and more accurate dimensions of the measurements of graphite flake lengths were obtained. Plates 1 to 6 show the micrographs of the as-cast unalloyed and copper alloyed grey cast iron with varying section thicknesses of 10mm, 25mm, and 75mm.

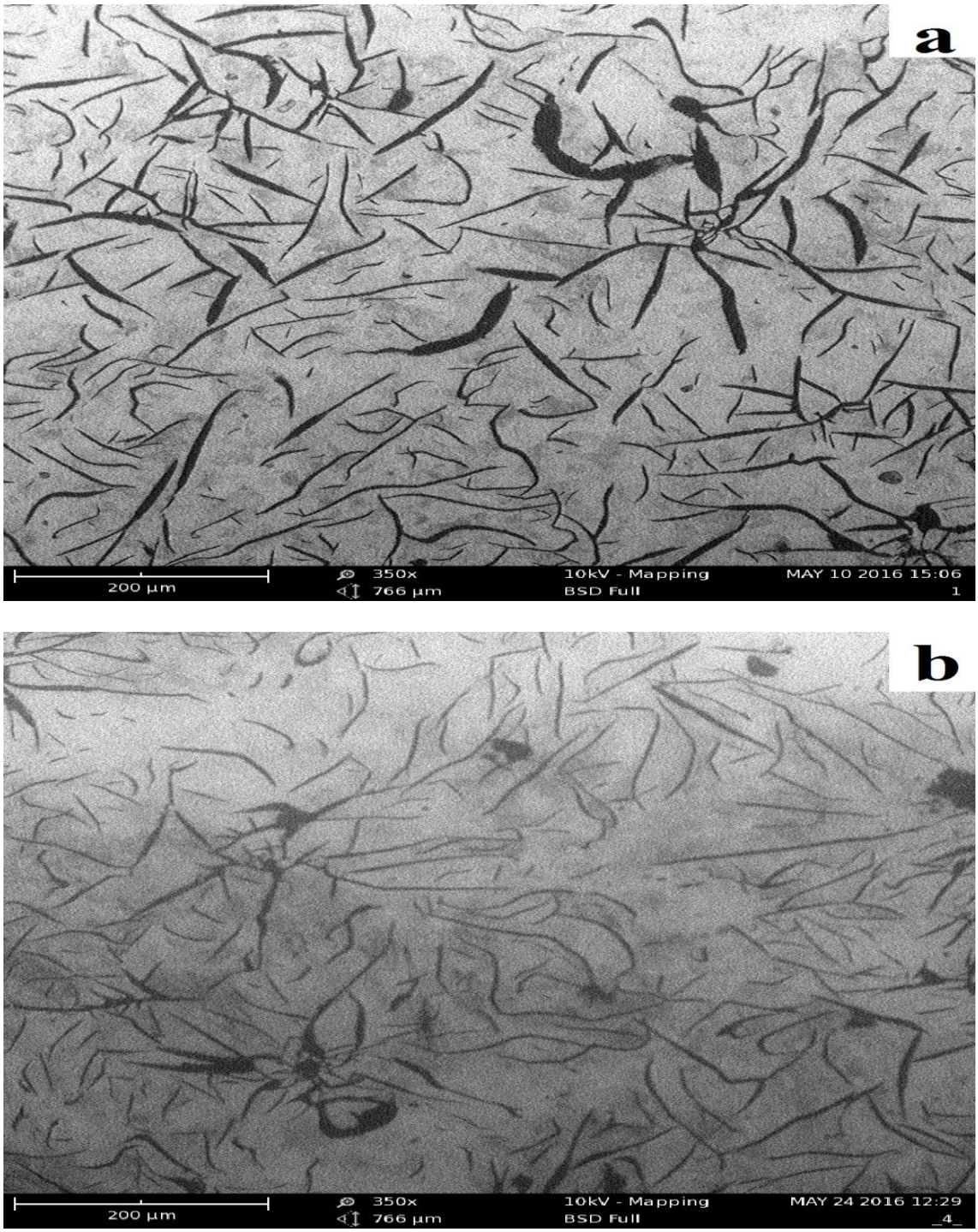
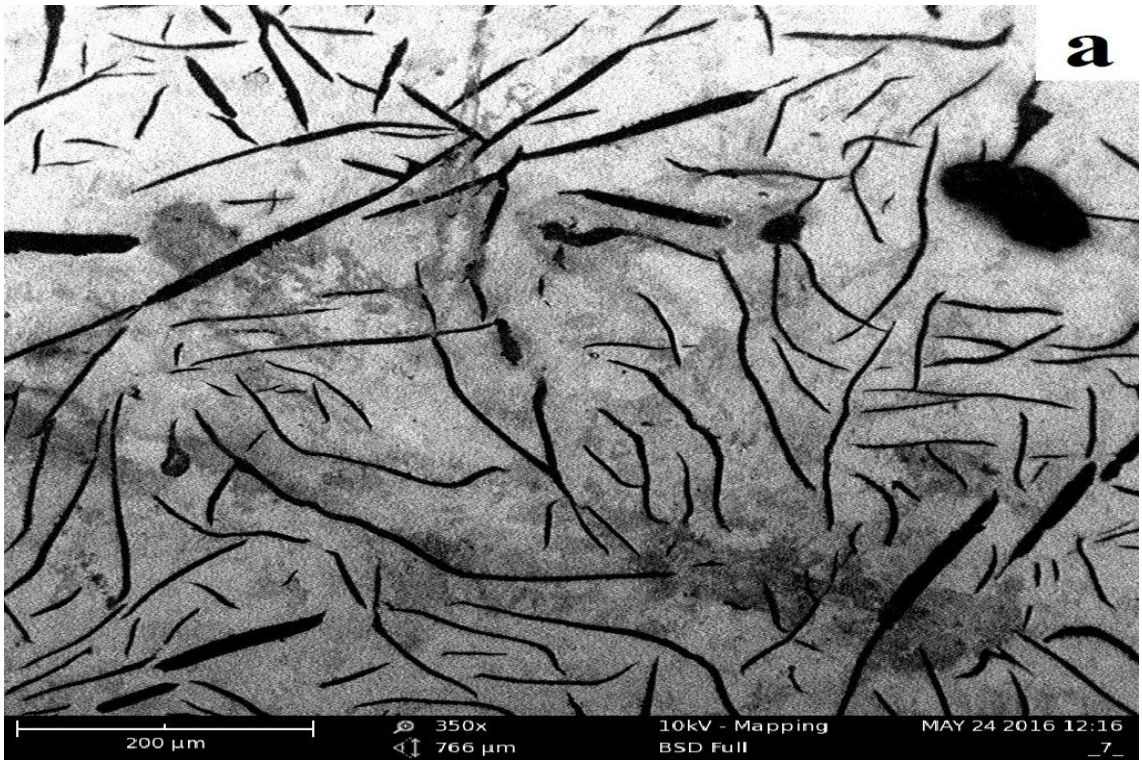


Plate 1.: SEM micrographs of the grey cast iron with 10mm section thickness. (a) 0.02% Cu; structure shows short type A graphite flakes in a ferrite matrix. (b) 0.55% Cu; fine and short hypereutectic type C (kish graphite) flakes in ferrite-pearlite matrix. 2% Nital etched (x350).



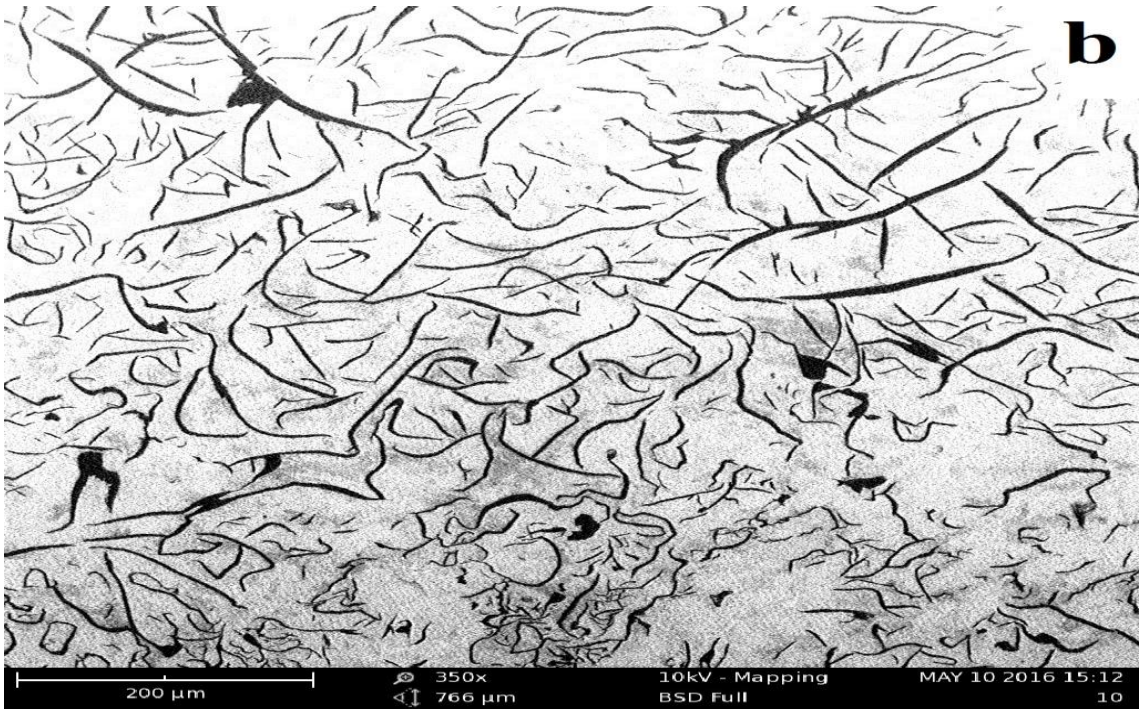


Plate 2.:SEM micrographs of the grey cast iron with 10mm section thickness. (a) 0.7% Cu; structure shows long graphite flakes in the ferrite-pearlite matrix. (b) 1.15% Cu; structure reveals type B (rosette graphite) flakes in the ferrite matrix. 2% Nital etched (x350).

Plate 1(a, b) and Plate 2(a, b) show the SEM microstructure of the 10mm section thickness grey cast irons with varied copper content. Plate 1(a) shows that the graphite flakes are short, which are uniformly distributed with random orientation in the ferrite matrix, thus they are categorised as type A flakes. Plate 1(b) shows the structure of grey cast iron with 0.55% Cu addition; the hypereutectic type C graphite flakes are observed to be fine and short in a ferrite-pearlite matrix. Plate 2(a) shows the microstructure of grey iron with 0.7% Cu. The structure shows a uniform distribution of graphite flakes in the ferrite-pearlite matrix. Plate 2(b) shows the microstructure of grey iron with 1.15% Cu. This structure reveals few large graphite flakes enveloped in uniformly distributed rosette graphite flakes (type B). The observed structures are consistent with the previous works of Taslicukur*et al*., (2012) and Sahu *et al*., (2014).

It was observed that the presence of copper decreases the growth and nucleation rate of the graphite flakeswhen added up to 0.7%, but increases their growth and nucleation rate when increased to 1.15%. This is as a result of the low graphitizing effect of copper at less than or equal to 0.7%, beyond this point up to 1.15%, copper has a high graphitizing effect in the grey cast iron.

The addition of copper at 0.55% and 0.7% was observed topromote the formation of pearlite (which accounts for the high strength, high hardness and low toughness obtained in the samples) while ferrite formation is favoured when copper is added up to 1.15% (which accounts for the low strength, low hardness and high toughness obtained in the samples). This ferritizing effect of copper observed in the present research is in agreement with Zou and Nakea, (2014).

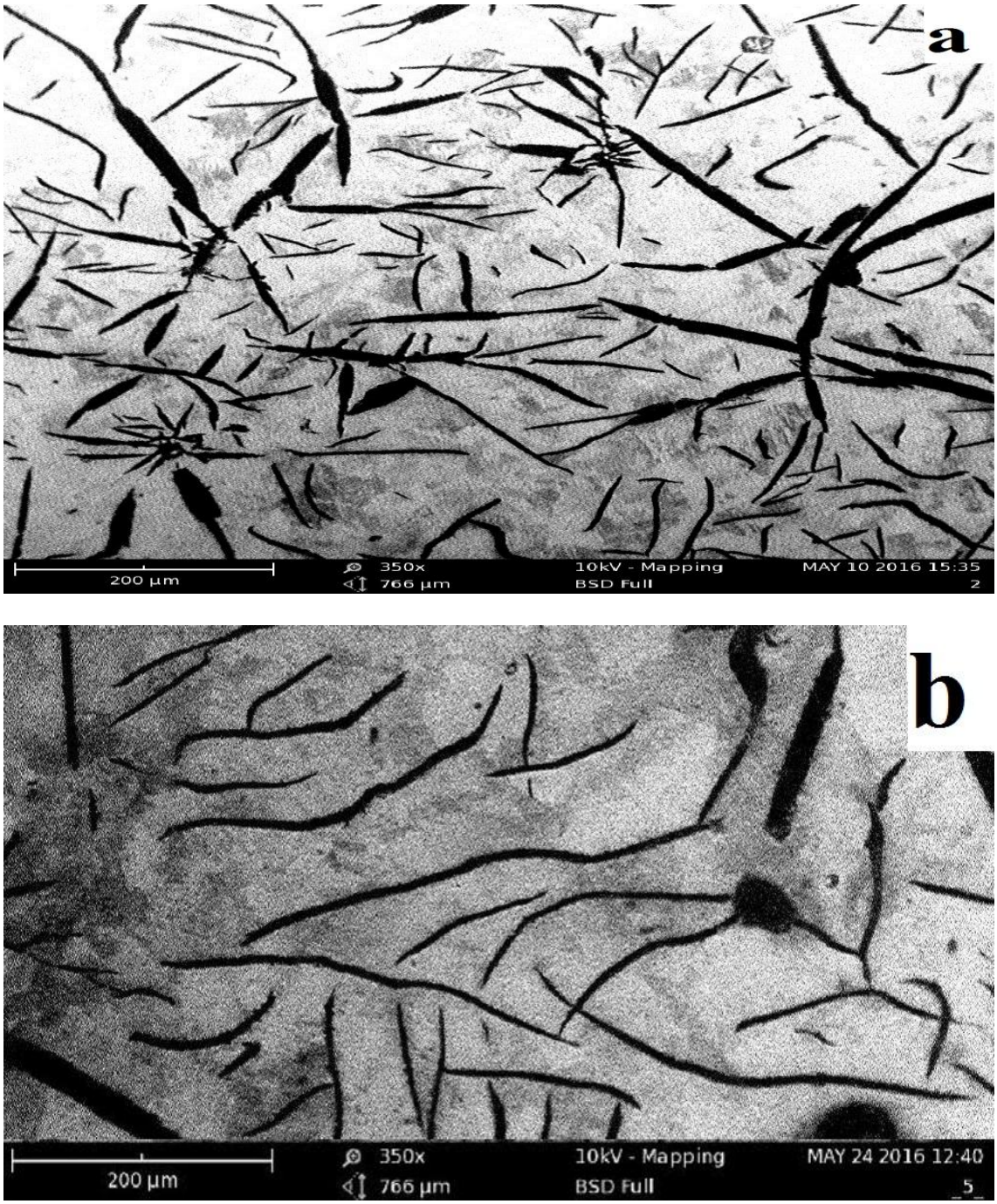


Plate 3.:SEM micrographs of 25mm thick grey cast iron specimens. (a) 0.02% Cu; structure shows large and coarse flakes with branches in the ferrite matrix (b) 0.55% Cu; structure shows coarse worm-like flakesin the ferrite-pearlite matrix. 2% Nital etched (x350).

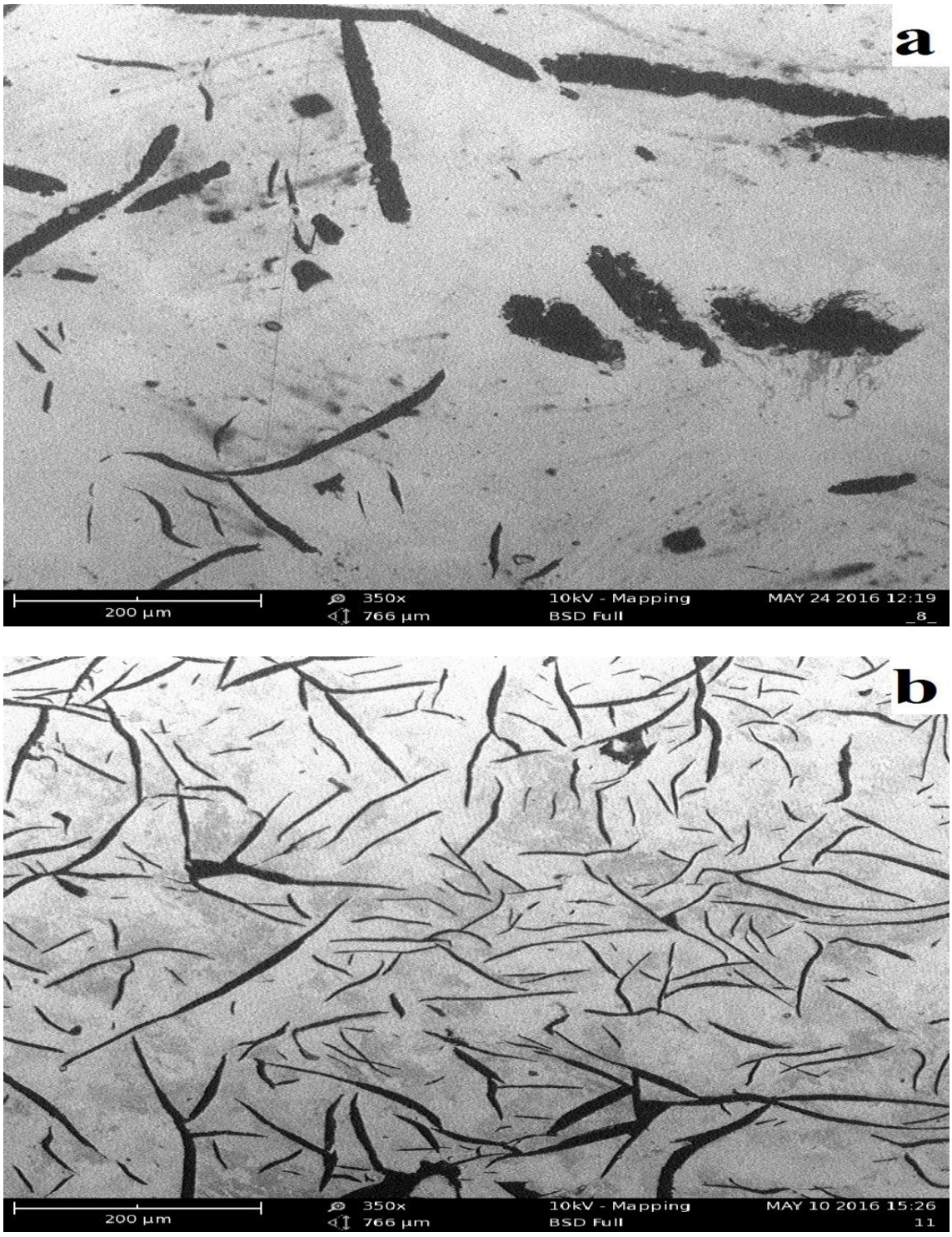


Plate 4.:SEM micrographs of the 25mm thick grey cast iron specimens; (a) 0.7% Cu; structure reveals hypereutectic coarse flakesin the matrix. (b) 1.15% Cu; structure shows hypoeutectic longer flakes in the ferrite matrix. 2% Nital etched (x350).

The microstructural formation of the 25mm section thickness grey cast iron castings Plates 3 and 4 revealed larger graphite flakes in all the specimens as a result of a decrease in the solidification time. Sahu *et al*., (2014) reported that slow cooling (a function of large section thickness) results in the formation of large/coarse graphite flakes. The present structures are also similar to the observed structures in the previous work of Hsu *et al*., (2000).

In the samples with copper, the flake length and thickness decreased with increasing copper content to 0.55% Plate 3(b) and from 0.55% to 0.7% Plate 4(a) as a result of pearlite phase enhancement and refinement by copper, which in turn increases the pearlite-ferrite ratio. However, as copper content increases from 0.7% to 1.15% Plate 4(b), the graphite flake length and thickness increase. This is attributed to the formation of more ferrite phases in the matrix. These results, as in the thinner sections (10mm) show that the graphite flake size in the structural matrix clearly explains the trend in the mechanical behaviour of the specimens.

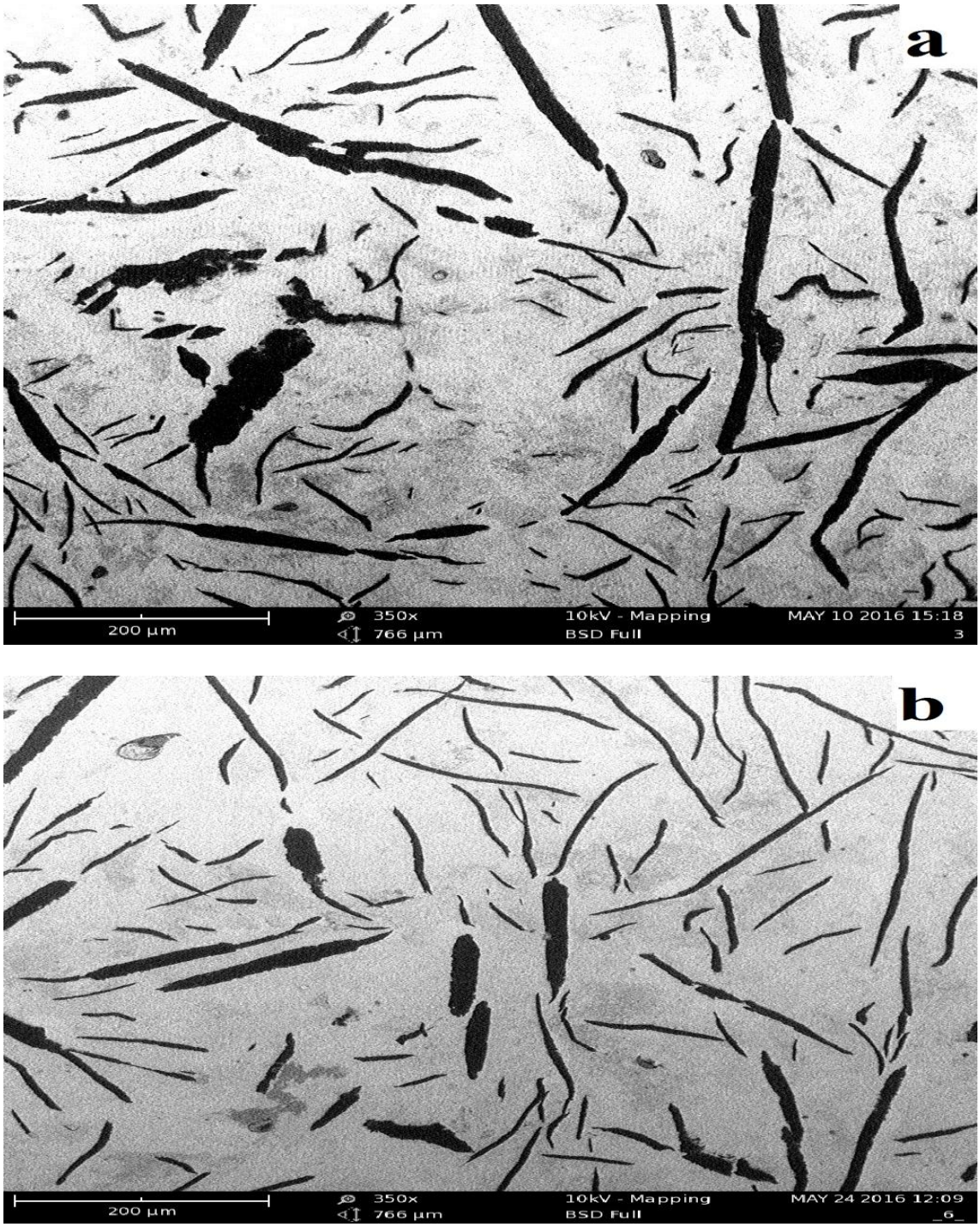


Plate 5.:SEM micrographs of 75mm thick grey cast iron specimens. (a) 0.02% Cu; structure shows non-uniform coarse flakes in the matrix structure. (b) 0.55% Cu; structure shows coarse worm-like flakes in the matrix. 2% Nital etched (x350).

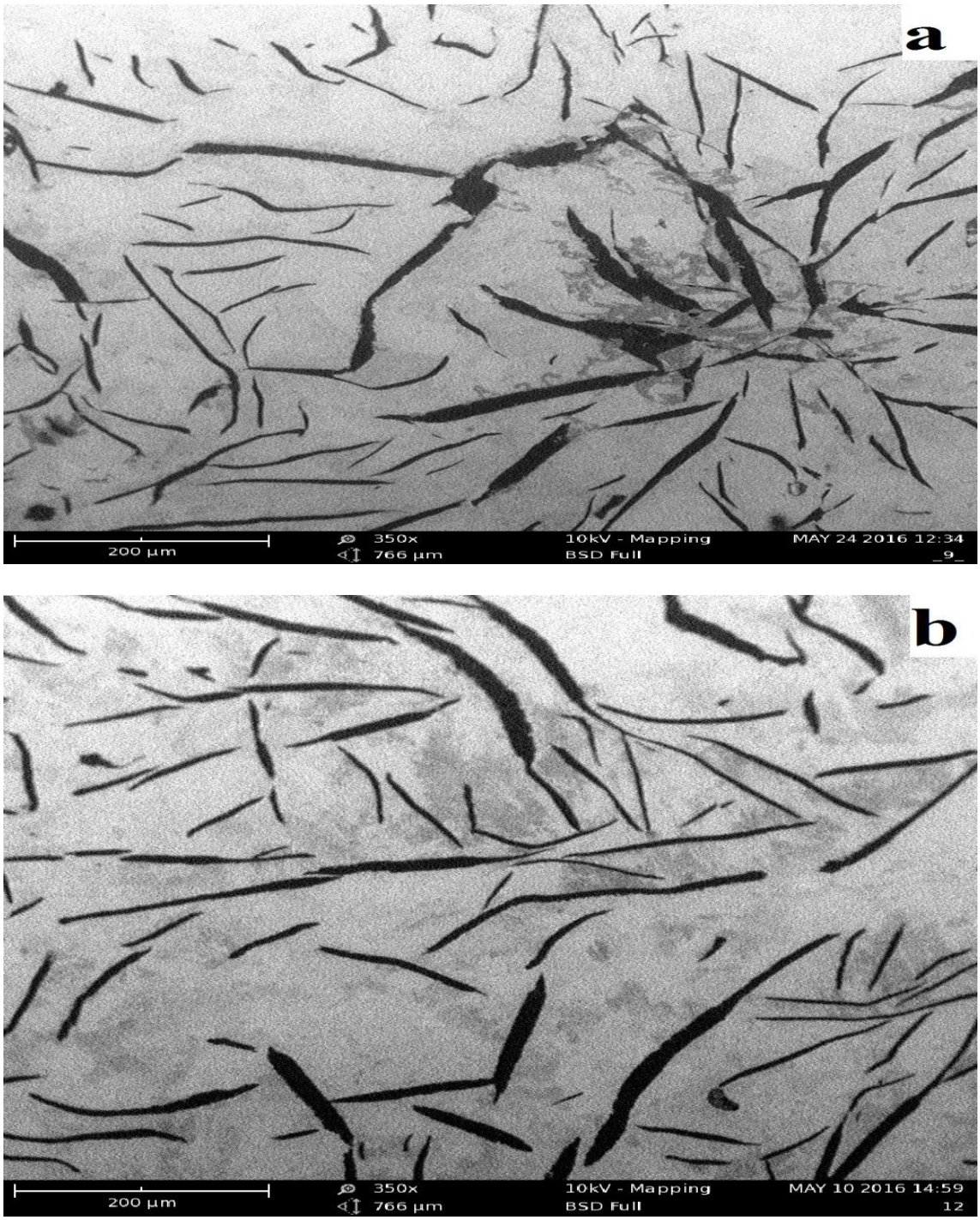


Plate 6.:SEM micrographs of 75mm thick grey cast iron specimens; (a) 0.7% Cu; structure shows hypereutectic type C graphite structure with random orientation in theferrite-pearlite matrix. (b) 1.15% Cu; the structure reveals unique features of coarse graphite flakes uniformly distributed in the matrix. 2% Nital etched (x350).

While examining the 75mm section thicknessgrey cast iron specimens Plates 5 and 6, it was observed that the graphite flakes in these specimens are much larger and have a greater variation in size than those of the specimens observed in the previous microstructures from the thinner samples due to longer solidification period. Plate 5(a) shows the microstructure of the specimen without copper. It was observed to have non-uniform coarse graphite flakes and fewer graphite flakes. Plate 5(b) shows the structure of the specimen with 0.55% Cu having coarse worm-like graphite flakes. When 0.7% Cu was added, the graphite flake morphology changed to a hypereutectic type C graphite structure with random orientation in the ferrite-pearlite matrix Plate 6(a). Plate 6(b) shows the microstructure of 1.15% Cu alloyed grey cast iron. The structure reveals unique features of coarse graphite flakes uniformly distributed in the matrix. The different morphologies of the flakes in each specimen account for the different mechanical behaviour exhibited by the specimens.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The effects of copper additionand section thickness on some mechanical properties and the morphology of graphite flakes in the produced unalloyed and copper alloyedgrey cast ironshave been investigatedusing microstructural analysis and mechanical properties tests. Based on the results obtained within the scope of the current investigation, the following conclusions were drawn;

- The section thickness has more effect on the graphite morphology than the copper addition, while the latter can be said to have affected the steel matrix of the grey cast iron than the graphite morphology.
- The SEM examination determined that, the addition of copper up to 0.7% led to a decrease in the graphite flake length but increased the graphite flake length when added up to 1.15% in all the section thicknesses.
- The addition of copper up to 0.7% enhanced the pearlite phase thereby increasing strength and hardness while decreasing toughness. However, when increased up to 1.15%, it increased the ferrite fraction in the matrix, thereby lowering strength and hardness while improving toughness.
- Fine and short graphite flakes were observed in the grey cast iron with 10mm section thickness while the grey cast iron with 25mm and 75mm sectionthickness contain large and extra-large graphite flakes respectively.
- Base on the mechanical properties obtained, the developed type B (rosette graphite) graphite flake having 85.95μm length in the 1.15% Cu grey cast iron with 10mm section thickness is recommended in applicationswhere strength and

toughness are required (making of products such as, engine blocks and cylinder heads).

5.2 Recommendations

Based on the research, the following recommendations are offered:

- Effect of copper addition (between 0.7% and 1.15%) on grey cast iron should be investigated to be able to determine the turning point of the influence of Cu on graphite morphology and mechanical properties of G.C.I.
- An image analyser should be used to measure the graphite flake length in order to obtain precise values.
- Other alloying elements should be looked into, particularly Ni, Mg and Ce.

5.3 Contribution to Knowledge

Although there are several documented researches on the effect of copper on the microstructure and mechanical properties of grey cast iron, to the author's best knowledge, the specific role copper plays on the graphite flake size is not well established. Therefore this work established that;

- The research further creates awareness on the role copper plays in the modification of graphite flakes in grey cast iron.
- Copper enhances the pearlite phase and reduces the length of graphite flakes in grey cast iron at a maximum addition of 0.7%. Beyond this level, it influences ferrite formation. Therefore, a range for the optimum value of Cu in grey cast iron was established.
- This material can support indigenous technology of spare part production for automotive industry such as engine blocks and brake components. The best casting properties of grey cast iron was displayed at 10mm section thickness.

REFERENCES

Adedayo, A.V. (2013). Relationship between graphite flake sizes and the mechanical properties of grey iron. *International Journal of Materials Science and Application, 2*(3), 94-98. doi:10.11648/j.ijmsa.20130203.14

Agunsoye, J.O., Hassan, S.B., Adeyemo, R.G and Odii, J.M. (2014). The Effect of copper addition on the mechanical and wear properties of grey cast iron. *Journal of Minerals and Materials Characterization and Engineering*, 2, 470-483. doi:http://dx.doi.org/10.4236/jmmce.2014.25048

Allen, D.K. (1969). *Metallurgy Theory and Practice*(1st ed., pp.270-290). Chicago: Americantechnical society.

Ambooken M.T. (2006). The Influence of Magnetic Austempering on Microstructure and Mechanical Properties of Austempered Ductile Cast Iron (ADI). Unpublished Master's Thesis.Dept.of Materials Science and Engineering, Wayne State University, Detriot, Michigan.

ASM Handbook.(2004). Metallography and Microstructures. Volume 9 pp 565-587. ASM International, Materials Park, Ohio, USA.

ASTMA247. (1990). *AnnualbookofASTMStandards* (*01*(02),pp 117-118). ASTM International, 100 Barr Harbor Drive, West Conshohocken, PA 19428-2959 USA.

ASTM A247. (2006). Standard test method for evaluating the microstructure of graphite in iron castings.*ASTM International*, 100 Barr Harbor Drive, West Conshohocken, PA 19428-2959 USA.

ASTM (2007a).Standard test method and definitions for mechanical testing of steel products.*ASTM International*, 100 Barr Harbor Drive, West Conshohocken, PA 19428-2959 USA.

ASTME-8.(1993).AnnualbookofASTMStandards, 3(01).*ASTM International*, 100 Barr Harbor Drive, West Conshohocken, PA 19428-2959 USA.

Ause, T.(2008). Evaluation of Hot-Bitumen Bath as Quenching Medium for Austempering of Steel and Ductile Cast Iron. Unpublished Ph.D. Dissertation. Dept. of Metallurgical and Materials Engineering, Ahmadu Bello University, Zaria, Nigeria.

Ashraf M.S. (2008). Effects of Heat Treatment and Alloying Elements of Characteristics of Austempered Ductile Iron.Unpublished PhD. Dissertation.Dept. of Metallurgical and Materials Engineering. University of Engineering and Technology Lahore – Pakistan.

Behnam, M.M.J., Davami, P and Varahram, N. (2010). Effect of cooling rate on microstructure and mechanical properties of grey cast iron. *MaterialsScience and Engineering*, *A528*(2), 583–588.doi:10.1016/j.msea.2010.09.087

Callister, W.D. (2007). *Material science and engineering: An introduction*(7th ed., pp.366-368). New York, NY: John Wiley & Sons, Inc.

Chakrabarti, A.K. (2005). *Casting technology and cast alloys* (pp.136). New Delhi: PHI Private Limited.

Choi, J.O., Kim, J.Y., Choi, C.O., Kim, J.K and Rohatgi, P.K. (2004). Effect of rare earth element on microstructure formation and mechanical properties of thin wall ductile iron castings. *Materials Science and Engineering A* 383, 323–333. doi:10.1016/j.msea.2004.04.060

Collini, L., Nicoletto, G and Konecna, R. (2008).Microstructure and mechanical properties of pearliticgrey cast iron. *Materials Science and Engineering*, A *488*(1-2), 529–539.

Das, A.K., Dhal, J.P., Panda, R.K., Mishra S. C. and Sen, S. (2013). Effect of Alloying Elements and Processing Parameters on Mechanical Properties of Austempered Ductile Iron. *Journal of Materials and Metallurgical Engineering,3*(1), 8-16.

Davis, J.R. (1996). Classification and Basic Metallurgy of Cast Irons.*American Society of Metal (ASM), Specialty Handbook Cast Irons,* 10-20.

De Campos, M.F., Rolim, L.C., Magina, P., Tavares, L., Kunioshi, C.T and Goldenstein, H. (2005). Texture and microtexture studies in different types of cast irons.*Materials Science and Engineering: A, 398*(1), 164-170.

Dommarco, R.C., Jaureguiberry, A.J., Sikora, J.A. (2006). Rolling contact fatigue resistance of ductile iron with different nodule counts and matrix microstructures. *WEAR, 261*(2), 172-179.

Global casting magazine. Retrieved March 21, 2016, from http://www.globalcastingmagazine.com/index.php/2013/12/10/futurepromising-for-high-strength-grey-iron/

Hsu, C-H., Shy, Y-H., Yu, Y-H andLee, S-C. (2000). Effect of austempering heat treatment on fracture toughness of copper alloyed greyiron. *Materials Chemistry and Physics,63*(2000) 75–81.

Hsu, C-H and Lin, K-T. (2011).A study on microstructure and toughness of copper alloyed and austemperedductile irons. *Materials science and engineering* A 528, 5706–5712. doi:10.1016/j.msea.2011.04.035

Hsu, C-H and Lin, K-T. (2014). Effects of Copper and Austempering on Corrosion Behaviour of Ductile Iron in 3.5 Pct Sodium Chloride. *Metallurgicaland Materials Transactions A* 45, 1517-1523. doi: 10.1007/s11661-013-2059-2

Khanna, O.P. (2002). *A textbook of Foundry Technology*(9th ed., pp.431). New Delhi: DhampartRai Publications

Krause, D.E. (1969). Gray Iron- A unique engineering material. Gray, Ductile and Malleable Iron Castings – Current Capabilities, ASTM STP 455, *American Society for Testing and Materials*, Philadelphia, pp. 3-28.

Kumar V. and Kumar A. (2013). Comparison of Structure and Properties of Semi-Solid Casting and Conventional Casting of Grey Cast Iron. *Transactions of 61st Indian Foundry Congress,* pp. 1-5.

Mikhailov A.M (1990). *Metal casting*(pp. 159, 163). Moscow: Mir Publishers

Millis, K. D. (1972). The future and development of spheroidal graphite cast iron. *Journal of British Foundryman*: pp.6 – 8.

Moonesan, M., Raouf, A.H., Madah, F. and Zadeh, A.H. (2012).Effect of alloying elements on thermal shock resistance of grey cast iron. *Journal of Alloys and Compounds*, 520, 226-231.doi:10.1016/j.jallcom.2012.01.027

NTE (2014). *2014 National trade estimate report onforeign trade barriers in Nigeria.* Retrieved February 15, 2015 from http://www.ustr.gov/about-us/press-office/reports-and-publications/2014-NTE-Report

Pevec, M., Grega, O., Potrc, I and Sraml, M. (2014).Elevated temperature low cycle fatigue of grey cast iron used for automotive brake discs. *Engineering Failure Analysis.* 42, 221-230. doi:http://dx.doi.org/10.1016/j.engfailanal.2014.03.021

Pluphrach,G. (2010). Study of the effect of solidification on graphite flakes microstructure and mechanical properties of an ASTM a-48 grey cast iron using steel molds. *Songklanakarin Journal of Science and Technology*, *32*(6), 613-618.

Sahu, S., Bhat, M.N., Kumar, A., Pratik, A and Kumar A. (2014). Effect of section thickness on the microstructure and hardness of grey cast iron(A Simulation Study).*International Journal of Engineering Research &Technology*, *3*(7), 35-40.

Smith, W. (1981).*Structure and Properties of Engineering alloys*(pp.315-340). London: Butterworth

Soiński, M.S. and Góraj, J. (2009). The Influence of cerium mixture addition on the structure of cast Iron containing about 5% aluminium. *Archives ofFoundry Engineering*, 9, 215-218.

Taslicukur, Z., Altug, G.S., Polat, Ş., Atapek, Ş. H and Turedi, E. (2012). Characterization of microstructure and fracture behaviour of GG20 and GG25 cast iron materials used in valves. *Metal 2012*, 5, 23-25.

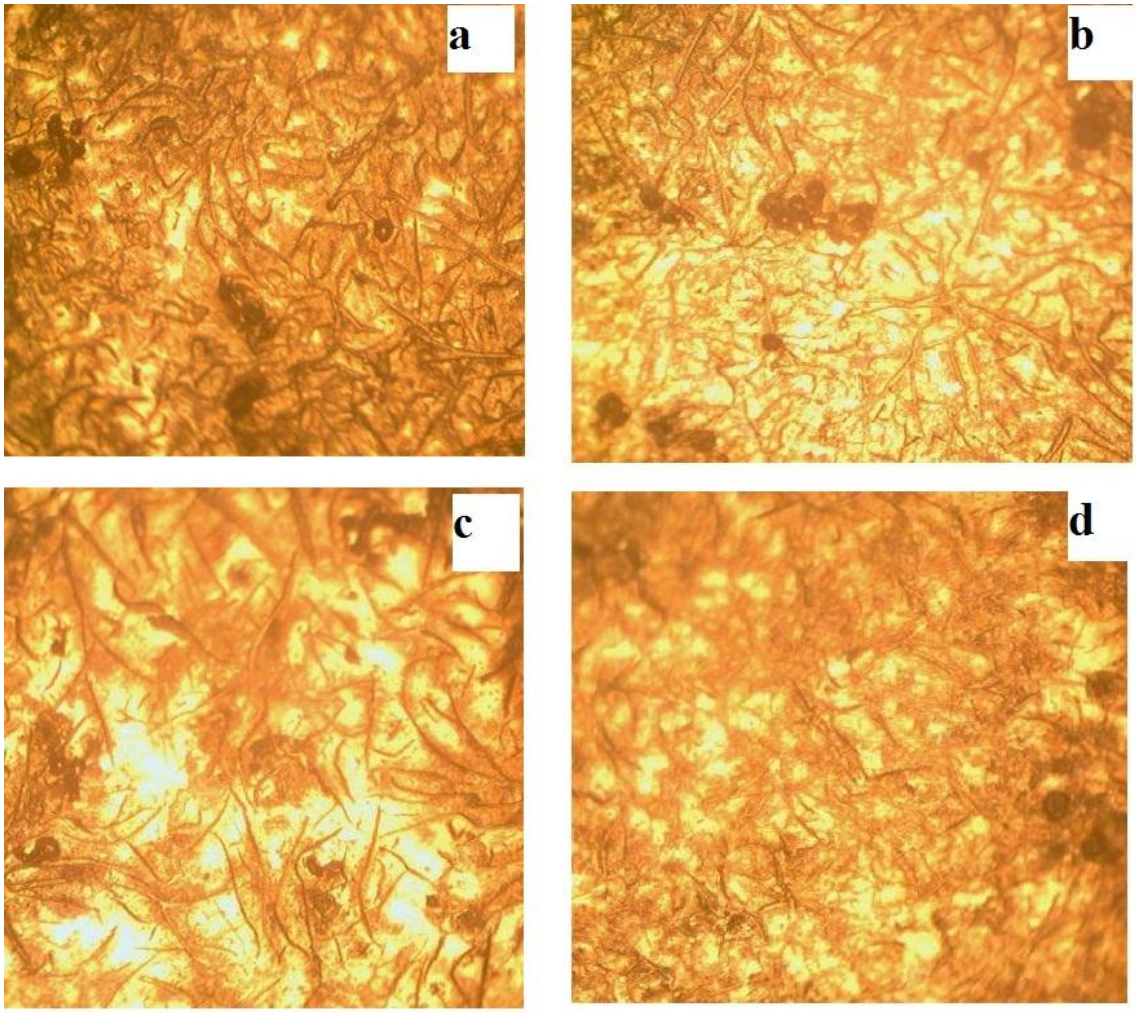
Uchimoto, T., Takagi, T and Abe, T. (2010). Electromagnetic non-destructive evaluation of graphite structures in flake graphite cast iron.*Materials Transactions*, *51*(6), 1114-1119.doi:10.2320/matertrans.F-M2010809

Ziółkowskia, E. and Wrona, R. (2007). Using fuzzy optimization method in calculation of charge burden to correct the chemical composition of metal melt. *Archives of Foundry Engineering*, 7, 183-186.

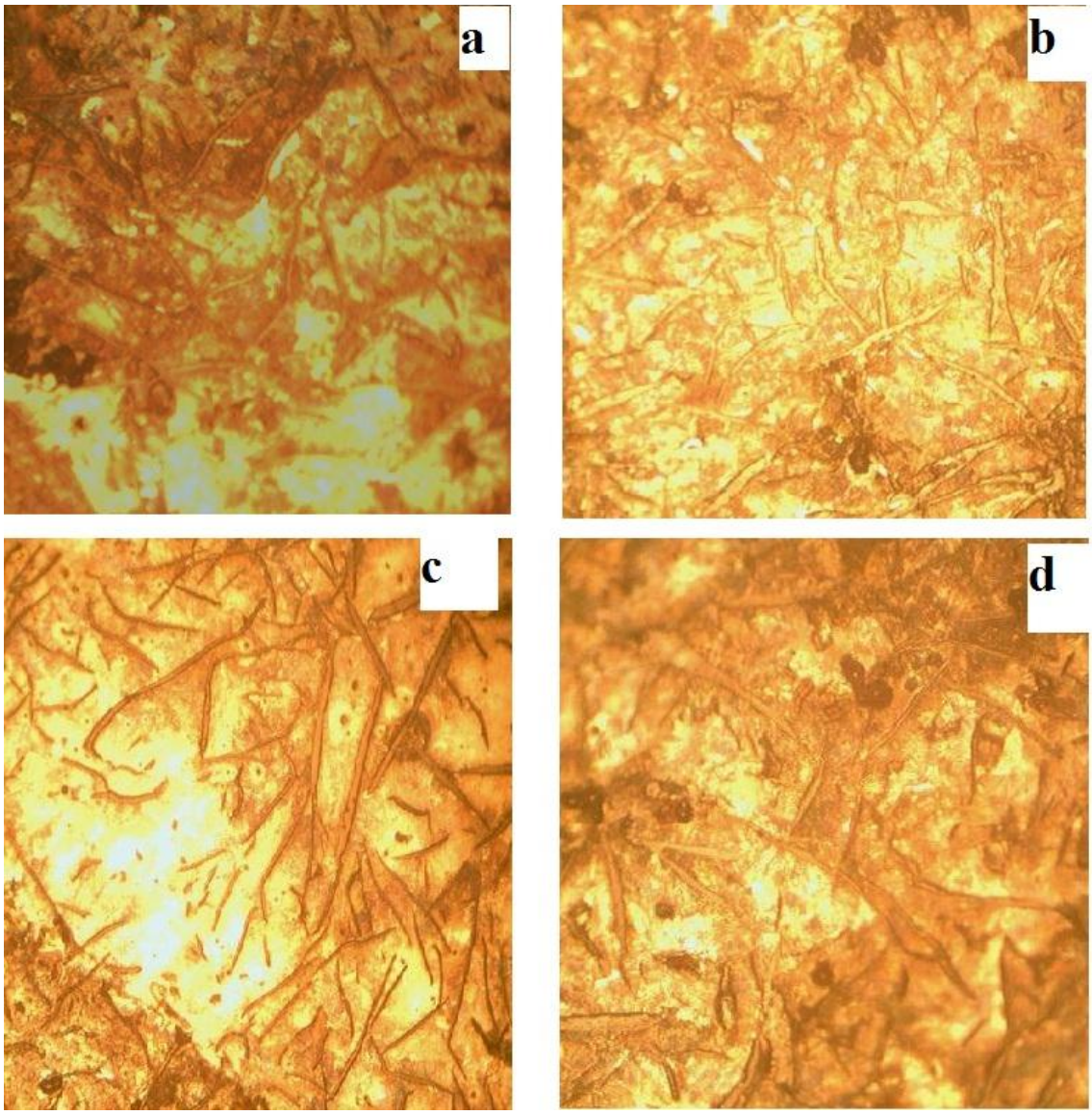
Zou, Y. and Nakea, H. (2014). Influence of boron on ferrite formation in copper added spheroidal graphite cast iron. *Journal of China Foundry*, *11*(4); 375-381.

APPENDIX A

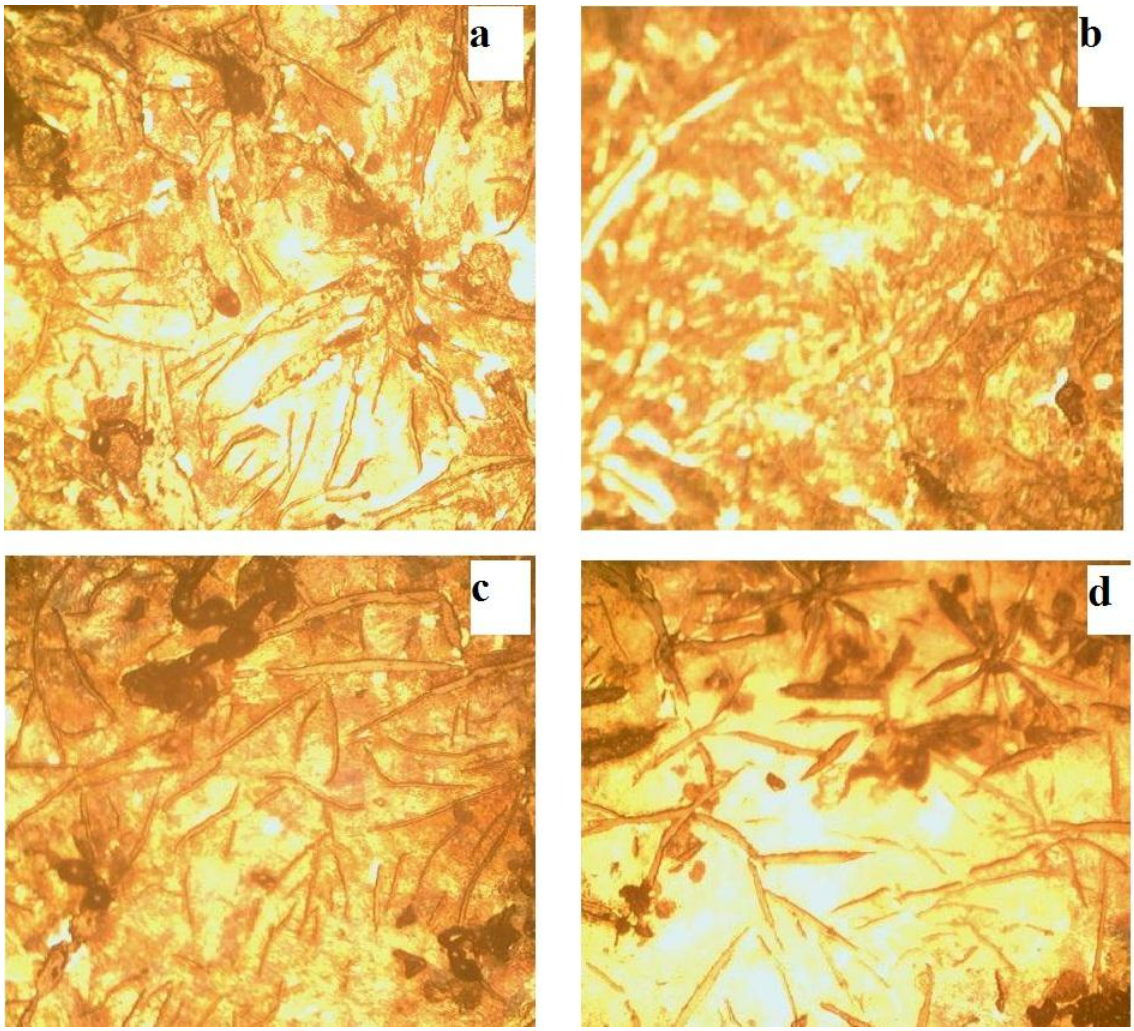
(OPTICAL MICROGRAPHS)



Micrograph A1: Optical Micrographs of grey cast iron with 10mm section thickness. (a) 0.02% Cu; (b) 0.55% Cu; (c) 0.7% Cu; (d) 1.15% Cu



Micrograph A2: Optical Micrographs of grey cast iron with 25mm section thickness. (a) 0.02% Cu; (b) 0.55% Cu; (c) 0.7% Cu; (d) 1.15% Cu



Micrograph A3: Optical Micrographs of grey cast iron with 75mm section thickness. (a) 0.02% Cu; (b) 0.55% Cu; (c) 0.7% Cu; (d) 1.15% Cu

APPENDIX B

Table B1: Graphite flake sizes

Heat Number	Grey cast iron specimen (mm)	Maximum flake length (µm)	Minimum flake length (µm)	Average flake length (µm)	ASTM A247 class size	Graphite flake count
Heat 1 (0.02% Cu)	**10**	148.65	45.95	81.35	4	243
	25	200	43.24	92.7	4	169
	75	176.49	36.04	103.51	4	179
Heat 2 (0.55% Cu)	**10**	94.59	40.54	64.86	5	
	25	124.59	29.73	87.57	4	100
	75	208.11	35.14	94.05	4	179
Heat 3 (0.7% Cu)	**10**	87.84	40.59	64.32	5	
	25	107.84	27.03	78.65	5	77
	75	112.16	37.84	84.32	4	134
Heat 4 (1.15% Cu)	**10**	110.81	43.24	85.95	4	
	25	154.05	43.24	95.14	4	187
	75	223.68	46.01	105.68	4	127

Table B2. Results of Mechanical Tests

Heat Number	Grey cast iron specimens (mm)	Tensile strength (N/mm^2)	% Elongation	Impact strength (KJ/m^2)	Hardness (HRC)
Heat 1 (0.02% Cu)	**10**	116.71	2.7	85.9	46
	25	90.19	2.83	91.64	43.9
	75	63.66	3.22	99.05	42.7
Heat 2 (0.55% Cu)	**10**	142.64	2.59	80.79	46.9
	25	127.36	2.62	90.71	45.2
	75	101.88	2.7	94.46	44.4
Heat 3 (0.7% Cu)	**10**	150.28	2.51	76.96	47.5
	25	132.45	2.56	87.24	46
	75	109.53	2.64	88.63	44.9
Heat 4 (1.15% Cu)	**10**	111.41	2.85	89.65	44.4
	25	71.62	3.1	96.20	42.8
	75	58.36	3.35	107.13	40.1