KWAME NKRUMAH UNIVERSITY OF SCIENCE AND TECHNOLOGY,
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COLLEGE OF ENGINEERING
DEPARTMENT OF MATERIALS ENGINEERING.

TOPIC:
APPRAISAL OF LOCALLY MANUFACTURED STEEL BALLS FOR USE AS
ORE GRINDING MEDIA

A thesis submitted to the Materials Engineering Department, Kwame Nkrumah
University of Science and Technology, Kumasi in partial fulfilment of the
requirement for the Bsc Degree in Materials Engineering.

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DECLARATION

We hereby declare that this project “entitled” Appraisal Of Locally Manufactured Steel Balls To Be Used As Ore Grinding Media and research work was personally done by the students mentioned below under supervision by a lecturer and to the best of our knowledge, it contains no material previously published by another person or material except where due acknowledgement has been made in the text. It is being submitted as a final year project in partial fulfillment in awarding B.Scs. Degree in Materials Engineering in Kwame Nkrumah University of Science and Technology in Kumasi.

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ABSTRACT

This project presents the analysis of microstructure, chemical composition, and hardness of the grinding steel balls. Three (3) samples of steel balls were obtained from West African Forging Limited. Part of this steel balls were cut in which microstructure, chemical composition and hardness (Rockwell) were determined in the order as stated above to aid in the analysis of the grinding steel balls. After the analysis, it was observed that there was a steep hardness gradient which indicates that wear will occur rapidly. Although the composition was in their right proportion. Heat treatment was performed on the samples 100mm, 80mm, and 50mm of which they were heated to 810°C, this temperature was maintained (heating time) for 90mins, 60mins, and 45mins respectively. It was then followed by quenching in two different quenchants (water and oil). The samples were again heated (tempering temperature) to 160°C which was also maintained (soaking time) for 60mins, 50mins, and 45mins respectively. Hardness test was performed on the samples using hardness tester. After the experiment, it was observed that the change in gradient was not rapid which indicates that wear will not be very rapid. We recommend that the right heat treatment should be done on the balls to increase the hardness on the surface by decrease in the hardness gradient to reduce wear rate.
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CHAPTER ONE

1.0 INTRODUCTION

1.1 BACKGROUND

Steel balls are valuable commodities widely used in the mining industries for grinding ore. The mining industry strongly depends on the comminution operations to promote mineral liberation. This stage is characterized by considerable consumption of power, as approximately only 10% of the power consumed is effectively spent in particles breakage (Massola et al., 2016). Although there is some divergence regarding cost composition, the literature is unanimous in reporting that comminution may represent the highest cost in mining (Massola et al., 2016). ‘Radziszewski states that typical operational costs may be divided into extraction (30–70%), separation (5–20%), and comminution (30–50%); the latter being estimated at 50% due to power consumption and 50% due to the consumption of lifters and grinding media’ (Massola, 2016).

The mills most used in mineral processing plants are the tumbling mills – a cylindrical metal housing, internally coated, and partially filled with ore, water and grinding media, which rotates around its horizontal axis. The grinding media may be the ore itself (autogenous grinding), bars, balls, or cylpebs, or even the ore itself together with a small amount of balls (semi-autogenous grinding)

Steel balls work on a principle of impact and attrition. Size reduction of ore is done by the impact. Therefore the steel ball needs to possess some properties such as hardness, toughness and wear resistance. If these properties are in their right proportions, the steel balls are not expected to fail early.

However, locally manufactured steel ball companies now faces stiff competition from imports of the same product that is coming in with better quality. There is a need to
counter this competition by producing steel balls that are of at least the same quality or better. The chemical composition of the locally manufactured steel balls are already in place after the chemical composition analysis. What is required is the heat treatment cycle which include quenching and tempering process ideal for the developed ball to give the desired results.

1.2 PROBLEM STATEMENT

In mining process, precious ores are imbedded in the rocks, which is passed through different stages before they are extracted. Stages like crushing, grinding and milling of the ore is involved.

Over the years, large scale-mining companies in Ghana have imported steel grinding media from overseas. The importing of steel balls into the country leads to loss of foreign exchange. Steel balls have been produced locally to reduce the importation of steel balls. However, the locally manufactured steel balls tends to fail early causing financial loss to companies.

1.3 AIM AND OBJECTIVES

The aim of this project is to appraise locally manufactured steel balls.

i. The objectives are;

ii. To analyze the microstructure of steel balls.

iii. To analyze the chemical composition of the steel balls.

iv. To analyze the mechanical properties of the steel balls.

v. To improve on the mechanical property (hardness) of the steel balls.

vi. Recommend alternative method of increasing the mechanical properties (hardness).
1.4 METHODOLOGY.

In order to assess and upgrade the performance and mechanical properties of steel balls, the following methods were used.

Firstly, chemical analysis was performed on the steel balls using mass spectrometer (Angstrom V-950) from Tema Steel Company. Also, microstructural analysis was performed on the steel balls. Metallurgical microscope from KNUST, MATERIALS LAB was used to analyze the microscopic structure of the steel balls. Again, hardness test was performed on the various steel balls with Rockwell hardness tester (AI-RAS 369-2008/09) from West African Forging Limited. Furthermore, heat treatment (quenching and tempering) was performed on cut samples from the steel balls which were followed by hardness test on the various samples. Hardness tester (S/N:MH0110091312) from KNUST, MATERIALS LAB was used to analyze the hardness of the steel balls after the heat treatment of the steel balls.

1.4.1 Scope Of Work

This project is focused on the analysis of samples of locally manufactured steel balls obtained from West African Forging Limited used for milling and grinding of ore. Also to compare properties of the steel balls with standard and where necessary, perform heat treatment to improve properties of local steel balls.
CHAPTER TWO

LITERATURE REVIEW

2.0 INTRODUCTION

2.1 MINING OPERATIONS

Mining is the extraction of valuable minerals or other geological materials from the earth usually from an ore body, lode, vein, seam and placer deposits. These deposits form a mineralized package that is of economic interest to the miner. (EG Kelly and DJ Spottiswood, 1982). Ores recovered by mining include metals, coal, oil shale, gemstones, limestone, chalk, dimension stone, rock salt, potash, gravel, and clay. Mining is required to obtain any material that cannot be grown through agricultural processes, or created artificially in a laboratory or factory. Mining in a wider sense includes extraction of any non-renewable resource such as petroleum, natural gas, or even water.

The grinding of solid matters occurs under exposure of mechanical forces that trench the structure by overcoming of the interior bonding forces. After the grinding the state of the solid is changed: the grain size, the grain size disposition and the grain shape. (EG Kelly and DJ Spottiswood, 1982).

Milling also refers to the process of breaking down, separating, sizing, or classifying aggregate material. For instance rock crushing or grinding to produce uniform aggregate size for construction purposes, or separation of rock, soil or aggregate material for the purposes of structural fill or land reclamation activities. Aggregate milling processes are also used to remove or separate contamination or moisture from aggregate or soil and to produce "dry fills" prior to transport or structural filling.
2.1.2 Types Of Milling Machines

In ore materials processing a **grinder** is a machine for producing fine particle size reduction through attrition and compressive forces at the grain size level. The following are some of the milling machines used in reducing particle sizes in material processing:

1. **Ball mill**

A typical type of fine grinder is the ball mill shown in Fig 1. A slightly inclined or horizontal rotating cylinder is partially filled with steel balls, which grind material to the necessary fineness by friction and impact. Ball mills normally operate with an approximate ball charge of 30% of steel balls. Ball mills are characterized by their smaller (comparatively) diameter and longer length, and often have a length 1.5 to 2.5 times the diameter. The feed is at one end of the cylinder and the discharge is at the other. Ball mills are commonly used in the manufacture of Portland cement and finer grinding stages of mineral processing, one example being the Sepro tyre drive Grinding Mill. Industrial ball mills can be as large as 8.5 m (28 ft) in diameter with a 22 MW motor. (**ABB Communications, 2010**)

However, small versions of ball mills can be found in laboratories where they are used for grinding sample material for quality assurance.

![Figure 1.Operation of ball mill](image-url)
2. Autogenous mill

Autogenous or autogenic mills are so-called due to the self-grinding of the ore: a rotating drum throws larger rocks of ore in a cascading motion which causes impact breakage of larger rocks and compressive grinding of finer particles. It is similar in operation to a Semi-Autogenous Grinding mill as described below but does not use steel balls in the mill. Also known as ROM or "Run of Mine" grinding.

3. Sag mill

SAG is an acronym for Semi-Autogenous Grinding. SAG mills are autogenous mills but use grinding balls like a ball mill as shown in Fig 2. A SAG mill is usually a primary or first stage grinder. SAG mills use a ball charge of 8 to 21% (Strohmayr et al). The largest SAG mill is 42’ (12.8m) in diameter, powered by a 28 MW (38,000 HP) motor. (Van de Vijfeijken, Maarten, October 2010) and a power of 35 MW (47,000 HP) has been designed.

Attrition between grinding balls and ore particles causes grinding of finer particles. SAG mills are characterized by their large diameter and short length as compared to ball mills. The inside of the mill is lined with lifting plates to lift the material inside the mill, where it then falls off the plates onto the rest of the ore charge. SAG mills are primarily used at gold, copper and platinum mines with applications also in the lead, zinc, silver, alumina and nickel industries.
2.2 STEELS

Steel is an alloy of iron and other elements, primarily carbon. Because of its high tensile strength and low cost, it is a major component in buildings, infrastructure, tools, ships, automobiles, etc.

Steel base metal is iron, which is able to take on two crystalline forms (allotropic forms), body centered cubic (BCC) and face centered cubic (FCC), depending on its temperature. It is the interaction of those allotropes with the alloying elements, primarily carbon that gives steel and cast iron their range of unique properties. In the body-centred cubic arrangement, there is an iron atom in the center of each cube, and in the face-centred cubic, there is one at the center of each of the six faces of the cube.

In pure iron, the crystal structure has relatively little resistance to the iron atoms slipping past one another, and so pure iron is quite ductile, or soft and easily formed. In steel, small amounts of carbon, other elements, and inclusions within the iron act as hardening agents that prevent the movement of dislocations that otherwise occur in the crystal lattices of iron atoms.
The carbon in typical steel alloys may contribute up to 2.14% of its weight. Varying the amount of carbon and many other alloying elements, as well as controlling their chemical and physical makeup in the final steel (either as solute elements, or as precipitated phases), slows the movement of those dislocations that make pure iron ductile, and thus controls and enhances its qualities. These qualities include such things as the hardness, quenching behavior, need for annealing, tempering behavior, yield strength, and tensile strength of the resulting steel.

2.2.1 Classification Steels

1. Plain carbon steels

Plain carbon steels are composed simply of iron and carbon as their main constituents. The study of the structure of steels must start with the iron-carbon equilibrium diagram. Many of the basic features of this system influence the behavior of even the most complex alloy steels. For example, the phases found in simply binary Fe-C system persist in complex steels but it is necessary to examine the effects alloying elements have on the formation and properties of these phases.

The iron-carbon diagram provides a valuable foundation on which to build the knowledge of both plain carbon and alloy steels.
The steel portion refers to that of the iron-carbon diagram of use in the heat treatment of plain carbon steels.

Those steels with less than 0.83wt% carbon are referred to as hypo-eutectoid steels whilst those with more than 0.83wt% carbon are known as hyper-eutectoid steels. There exists various micro constituents present in plain carbon steels which are ferrite, cementite, pearlite and austenite.

**Ferrite**

It is ductile and the softest and form solid solution of carbon in body centered cubic (BBC) $\alpha$-iron containing a maximum of 0.04wt% carbon at 695$^\circ$C.
**Cementite**

It is the hardest and most brittle with the formula $\text{Fe}_3\text{C}$ and may exist usually as grain boundary film, or as a constituent of the eutectoid pearlite. It is formed in various combinations with ferrite and pearlite since its carbon content is 6.67wt% carbon.

**Pearlite**

The eutectoid structure consisting of alternate laminations of ferrite and cementite is formed by the breakdown of the austenite solid solution at 695°C. It contains 0.83wt% carbon. It possesses physical properties that are between those of very hard cementite constituent and the very soft ferrite constituent.

**Austenite**

It is a soft, ductile and non-magnetic face centered cubic $\gamma$-iron containing a maximum of 1.7wt% carbon at the upper critical range and may also occur at room temperature by adding special alloys to the metal. Some stainless steels, for instance, show austenite at room temperature.

2. **Alloy steels**

**Alloy steel** is steel that is alloyed with a variety of elements in total amounts between 1.0% and 50% by weight to improve its mechanical properties. Alloy steels are divided into two groups: low-alloy steels and high-alloy steels. The difference between the two is somewhat arbitrary: Smith and Hashemi define the difference at 4.0%, while Degarmo, et al 2007, define it at 8.0%.

However, the term "alloy steel" is the standard term referring to steels with *other* alloying elements added deliberately *in addition to* the carbon. Common alloyants include manganese (the most common one), nickel, chromium, molybdenum,
vanadium, silicon, and boron. Less common alloyants include aluminum, cobalt, copper, cerium, niobium, titanium, tungsten, tin, zinc, lead, and zirconium.

Alloying elements are added to achieve certain properties in the material. Alloying elements also have an effect on the eutectoid temperature of the steel.

2.2.2 Properties Of Steels.

Other materials are often added to the iron/carbon mixture to produce steel with desired properties. Nickel and manganese in steel add to its tensile strength and make the austenite form of the iron-carbon solution more stable, chromium increases hardness and melting temperature, and vanadium also increases hardness while making it less prone to metal fatigue.

To inhibit corrosion, at least 11% chromium is added to steel so that a hard oxide forms on the metal surface; this is known as stainless steel. Tungsten slows the formation of cementite, keeping carbon in the iron matrix and allowing martensite to preferentially form at slower quench rates, resulting in high speed steel. On the other hand, sulfur, nitrogen, and phosphorus are considered contaminants that make steel more brittle and are removed from the steel melt during processing.

The density of steel varies based on the alloying constituents but usually ranges between 7,750 and 8,050 kg/m³ (484 and 503 lb/cu ft), or 7.75 and 8.05 g/cm³ (4.48 and 4.65 oz/cu in). (Elert, Glenn, 2009)

2.2.3 Microstructural Properties.

In a narrow range of concentrations of mixtures of carbon and iron that make a steel, a number of different metallurgical structures, with very different properties can form. Understanding such properties is essential to making quality steel. At room
temperature, the most stable form of pure iron is the body-centered cubic (BCC) structure called alpha iron or α-iron. It is a fairly soft metal that can dissolve only a small concentration of carbon, not more than 0.005% at 0 °C (32 °F) and 0.021 wt% at 723 °C (1,333 °F).

When steels with exactly 0.8% carbon (known as a eutectoid steel), are cooled, the austenitic phase (FCC) of the mixture attempts to revert to the ferrite phase (BCC). The carbon no longer fits within the FCC austenite structure, resulting in an excess of carbon. In a hypereutectoid composition (greater than 0.8% carbon), the carbon will first precipitate out as large inclusions of cementite at the austenite grain boundaries until the percentage of carbon in the grains has decreased to the eutectoid composition (0.8% carbon), at which point the pearlite structure forms. (Smith & Hashemi, 2006).

As the rate of cooling is increased the carbon will have less time to migrate to form carbide at the grain boundaries but will have increasingly large amounts of pearlite of a finer and finer structure within the grains; hence the carbide is more widely dispersed and acts to prevent slip of defects within those grains, resulting in hardening of the steel. At the very high cooling rates produced by quenching, the carbon has no time to migrate but is locked within the face center austenite and forms martensite. Martensite is a highly strained and stressed, supersaturated form of carbon and iron and is exceedingly hard but brittle. Depending on the carbon content, the martensitic phase takes different forms. Below 0.2% carbon, it takes on a ferrite BCC crystal form, but at higher carbon content it takes a body-centered tetragonal (BCT) structure. There is no thermal activation energy for the transformation from austenite to martensite. Moreover, there is no compositional change so the atoms generally retain their same neighbors.

(Smith & Hashemi, 2006)
Martensite has a lower density (it expands during the cooling) than austenite does, so that the transformation between them results in a change of volume. In this case, expansion occurs. Internal stresses from this expansion generally take the form of compression on the crystals of martensite and tension on the remaining ferrite, with a fair amount of shear on both constituents. If quenching is done improperly, the internal stresses can cause a part to shatter as it cools. At the very least, they cause internal work hardening and other microscopic imperfections. It is common for quench cracks to form when steel is water quenched, although they may not always be visible.

2.3 HEAT TREATMENTS OF STEEL

1. Hardening

The use of this treatment will result in an improvement of the mechanical properties, as well as an increase in the level of hardness, producing a tougher, more durable item. Alloys are heated above the critical transformation temperature for the material, then cooled rapidly enough to cause the soft initial material to transform to a much harder, stronger structure. Alloys may be air cooled, or cooled by quenching in oil, water, or another liquid, depending upon the amount of alloying elements in the material. Hardened materials are usually tempered or stress relieved to improve their dimensional stability and toughness.

Steel parts often require a heat treatment to obtain improved mechanical properties, such as increasing hardness or strength. The hardening process consists of heating the components above the critical (normalizing) temperature, holding at this temperature for one hour per inch of thickness cooling at a rate fast enough to allow the material to transform to a much harder and stronger structure.
2. Tempering
Tempering is done to develop the required combination of hardness, strength and toughness or to relieve the brittleness of fully hardened steels. Steels are never used in as quenched condition. The combination of quenching and tempering is important to make tough parts.

This treatment follows a quenching or air cooling operation. Tempering is generally considered effective in relieving stresses induced by quenching in addition to lowering hardness to within a specified range, or meeting certain mechanical property requirements.

Tempering is the process of reheating the steel at a relatively low temperature leading to precipitation and spheroidization of the carbides present in the microstructure. The tempering temperature and times are generally controlled to produce the final properties required of the steel. The result is a component with the appropriate combination of hardness, strength and toughness for the intended application. Tempering is also effective in relieving the stresses induced by quenching.

3. Quenching
Quenching is the process of cooling a metal at a rapid rate from a predetermined high temperature by immersing the hot part in water, oil or another suitable liquid to transform the material to a fully hardened structure. This process is important as it is key in addressing the main challenge of manufacturing steel balls of high quality. The quenching media includes water, oil, etc. When hardening metallic materials, cooling is an important and decisive element in determining the properties of the part such as it hardness.
Cracking may happen during quenching or sometimes after quenching. The causes of cracking are:

1. Excessive amount of non-metallic inclusions in the steel
2. Improper selection of quenching medium – By using a quenching fluid which gives higher cooling rate than the one necessary may lead to cracking.
3. Uneven quenching in the quenching bath
4. Improper entry of the component into the quenching media causing eccentric and non-uniform cooling

2.4 PROCESSING OF STEEL BALLS

Steel balls are made from steels. There are two major types of processing steel balls, casting and forging process.

2.4.1 Cast Steel Balls.

Casting is one of the major process used in producing steel balls. Cast steel balls consist of low chromium cast iron balls, medium chromium cast iron balls, high chromium cast-iron grinding ball. Casting of steel balls is achieved by pouring molten metal into a mold to take the shape of the mold and allow it to solidify. The solidified part (steel ball) is broken out of the mold to complete the process.

2.4.2 Advantage Of Cast Steel Balls

i. High production rate
ii. Tooling is often less expensive than forge dies.
iii. Large range of alloy choices.
2.4.3 Limitation Of Cast Steel Balls

i. The casting process requires frequent monitoring and inspection to maintain quality and prevent defects.

ii. Often exhibit surface porosity than forged steel ball.

iii. Not as tough as forged steel balls (cannot withstand pressure and impact).

2.4.4 Forged Steel Balls.

Forging is one of the two major of processing a steel ball. Fig 4 shows how steel balls are forged. Forged steel balls consist of low carbon alloy steel, medium carbon alloy steel, high manganese steel, rare earth, and chromium molybdenum alloy steel balls. By forging it can eliminate the as-cast porosity and defects of metals in the smelting process and the microstructure is optimized. In addition to the relative simple shapes and can be rolled plated, profiles or welded parts, mostly use forging process. Forged steel balls have strong toughness, good wear resistance and not easy to be broken. Forged balls are produced by cut metal and placing it in a die to take the shape of the die. The die is forced together, forging the metal ball, causing it to take the spherical shape of the die cavity. Balls are finished and polished, before they are ready for their particular application.
2.4.5 Advantages Of Forged Steel Balls.

i. Good surface quality.

ii. Good impact resistance.

iii. Strong toughness.

iv. Good wear resistance and it’s not easy to be broken.

2.4.6 Limitations Of Forged Steel Balls

i. High expenditure for the machinery, dies, tools and personnel.

ii. The steel ball can get cracked or distorted if worked below a specified temperature limit.

iii. The maintenance cost of forging dies is also high.

2.5 MATERIALS CHARACTERISATION

It is the process by which a material’s structure and properties are probed and measured. It is a fundamental process in the field of materials science, without which no scientific understanding of engineering materials could be ascertained.
2.5.1 Hardness Test

Hardness is the measure of how resistant solid matter is to various kinds of permanent shape change when compressive forces are applied. Hardness testing measures a material’s strength by determining resistance to penetration. Hardness testing is usually performed using attest machines equipped with an indenter that is forced into the test material over a certain amount of time. There are three (3) hardness testing methods which are usually used. They are Brinell, Vickers and Rockwell hardness test.

The Brinell hardness test consists in indenting the metal surface with a 10-mm diameter steel or tungsten carbide ball at a load range of 500-3000 kg, depending on hardness of particular materials. The load is applied for a standard time (10-30s), and the diameter of the indentation is measured. Giving an average value of two readings of the diameter of the indentation at right angle. (Maithem H-Rasheed)

Vickers hardness test uses a square-base diamond pyramid as the indenter with the included angle between opposite faces of the pyramid of 136°.

The Vickers hardness number (VHN) is defined as the load divided by the surface area of the indentation.

This test is preferable to the Brinell test where hard materials are concerned, as it uses a diamond indenter. (Diamond is the hardest material known - approximately 6000 HB). Standard loads are 5, 10, 20, 30, 50 and 100 kg. It is necessary to state the load when specifying a Vickers hardness number. (Maithem H-Rasheed)

The Rockwell tests constitute the most common method used to measure hardness and is widely used in industry as it is quick, simple and direct reading. In principle the
Rockwell hardness test compares the difference in depth of penetration of the indenter when using forces of two different values. That is, a minor force is first applied (to take up the backlash and pierce the skin of the component) and the scale are set to read zero. Then a major force is applied over and above the minor force and the increased depth of penetration is shown on the scales of the machine as a direct reading of hardness without the need for calculation or conversion tables. (Maithem H-Rasheed)

2.5.2 Chemical Analysis

It is the study of the chemical composition and structure of substances. There are two branches in analytical chemistry:

1. Qualitative analysis
2. Quantitative analysis.

Qualitative chemical analysis, branch of chemistry that deals with the identification of elements or grouping of elements present in a sample. The techniques employed in qualitative analysis vary in complexity, depending on the nature of the sample. It does not measure the amount of the substance, but rather looks at factors such as color, smell, texture, atomic structure.

Quantitative chemical analysis, branch of chemistry that deals with the determination of the amount or percentage of one or more constituents of a sample. Refers to analyses in which substances are identified or classified on the basis of their chemical or physical properties, such as chemical reactivity, solubility, molecular weight, melting point, radiative properties (emission, absorption), mass spectra, nuclear half-life, etc.
2.5.3 Microstructural Analysis

Microstructure Analysis focuses on the art and science of preparing, interpreting, and analyzing microstructures in engineered materials, to better understand materials behavior and performance.
CHAPTER THREE

3.1 METHODOLOGY

For the first experimental work, chemical analysis was performed on the various balls to acquire detailed information on the individual elements present in the grinding ball and the amount of each element. Furthermore, the microstructure of the various balls sizes were determined, which helped to know the phases present and the amount in which they occur in the balls. The last but not the least, surface hardness of the various balls were tested as well as the core hardness using the Rockwell Hardness testing machine respectively.

3.1.1 Materials Used.

The material samples that were used in the experiments were unused steel balls which were produced locally at West African Forging Limited. The material samples were in different sizes, that is, they were in different diameters. Three (3) main samples were used in the experiment. They are 100mm, 80mm, and 50mm steel grinding balls.

3.1.3 Determination Of Chemical Composition.

The chemical composition was performed at Tema Steel Company limited. Angstrom V-950 spectrometer was used to determine the chemical composition. The surface of the ball was polished ensuring that dust particles does not settle on the surface. The polished surface of the sample was placed on a boron disc in the spectrometer. The sample was the sparked on three (3) different points. The spectrometer is connected to a computer unit which displays the amount of element present on a monitor. The average of the three (3) was the taken and printed. The procedure was repeated for all the samples and the averages were taken.
3.1.4 Microstructural Analysis

The experiment was carried out at the materials engineering laboratory, KNUST. The following process were involved.

The three (3) samples were sectioned into 2 equal parts each. One parts were separated and were labelled ‘A’ and the others ‘B’. Coarse grinding using pedestal grinder were performed on the three(3) samples at the ends of each sample using size 100 Amery cloth to get uniform scratches on the surfaces with water to cool the sample. Successive medium and fine grinding were performed each on the two (2) end surfaces of the samples from size 400, 600, 800 and finally to size 1000 Amery cloth and finally washed thoroughly with water. Mechanical polishing were performed on a polishing cloth using aluminum oxide solution to wet the surface of the polishing cloth to acquire a mirror-like surface. The polished surfaces of the samples were dipped into Nital for 10 to 30 seconds and then rinsed with Ethanol. The samples were then air dried and cleaned with cotton wool. The microscopic examination stage was finally carried out to get the phases present in each sample under a metallurgical microscope.

3.1.5 Determination Of Hardness

The chemical composition was performed at West African Forging Limited. The following steps were applied in the process. A portion of the steel ball surface was grinded in a firmly tightened clamp. (To get smooth surface for the hardness test). One flat surface was placed on the plunger and tightened to a steel ball bearing. The nod was brought down and taken up again. As the nod goes up, the load goes up and vice versa. The principle the machine uses is that the balls indent the metal surface and an impression is made on the surface as the pressure is applied. The indentation is
made on three (3) different points and an average is taken. The same procedure was repeated at the opposite surface for the measurement.

3.1.6 Cut Sample From The Whole Steel Ball

The experiment was performed at West African Forging Limited. The following steps were applied in the process

The work piece was clamped on the EDM table. Axis or corrector was set for the electrode pipe to be used. The pipe was positioned on the very tip/surface of the grinding media. Kerosene was pumped into the EDM table. The program for the depth of the work piece was configured. The core of the grinding media was taken out. The ends of the extracted core were then grinded to acquire smooth for the hardness test.

3.1.6.1 Cut sample hardness test using Rockwell hardness tester.

The experiment was performed at West African Forging Limited. The following steps were applied in the process.

The length of the whole sample was measured. Half of the sample was taken to find the first indentation, C₁. This length, was also divided into two to find the second indentation, C₂. Then half the length of C₂ was taken to be C₃. Half the length of C₃ was taken to be C₄. These were done for the 50mm ball. But for the 100mm and 80 mm balls, the whole length were divided into 2 for C₁, and 10mm was subtracted from C₁ to get C₂, till the last hardness was measured.
3.1.6 Heat Treatment Of The Samples.

The samples were heated to 810°C to be fully austenized. The 50mm samples were removed from the furnace after 45mins with sample A, quenched in oil shown in table 2 below, and sample B was quenched in water shown in table 3. Also 80mm sample were quenched after 1hr in oil and water and 100mm samples were also removed and quenched in oil and water after 1hr 30mins respectively. The quenching was done by dipping one end into the quenchant and the other end suspended in air, this was done to have differentiate the hardness on the surface from the core. The 100mm, 80mm and 50mm samples were reheated to 160°C and were soaked for 1hr, 50mins and 45mins respectively and were air cooled. Table 2 below shows heat treatment on sample A, quenched in water and table 3 shows heat treatment performed on sample B, quenched in oil.

3.1.7 Hardness Test After Heat Treatment.

The hardness of the samples were measured using the universal hardness tester from the KNUST materials laboratory. After heat treatment of the various samples were performed, the surface of the sample were sand papered and hardness from different point were successively measured and recorded. This procedure was repeated for the remaining samples.
CHAPTER FOUR

4.1 RESULTS AND DISCUSSION

4.1.1 CHEMICAL ANALYSIS

The results yield after chemical composition analysis was performed on the three samples. From table 3, 4, and 5, it was observed that the carbon content of steels was in a range of 0.6 to 0.7 percent. Furthermore, the Cr content was between the ranges of 0.520 to 0.700. The content of Fe was also between the ranges of 96.800 to 97.55. Mn and S also was in a range between 0.702 to 0.850 and 0.002 to 0.037 respectively.

MICROSTRUCTURAL ANALYSIS

50MM STEEL BALL SIZE

Figure 5. Micrograph of ore steel grinding ball taken at the core.
Figure 6. Micrograph of steel grinding ball taken from the surface.

80MM STEEL BALL SAMPLE

Figure 7. Micrograph of forged steel grinding ball taken at the core.
80mm X 100a

**Figure 8.** Micrograph of forged steel grinding balls taken near the surface.

100MM STEEL BALL SAMPLE

**Figure 9.** Micrograph of steel grinding ball taken from the core.
From graph 1 below, the hardness (652 HB) of the grinding steel balls as received has higher hardness per the standard hardness for ore grinding media which is 600 to 650 HB), (J.S. MOEMA, et al, 2009), but a steep slope. This indicates that the hardenability of the ball is very low of which wear will be very rapid as hardenability refers to the ability of metal resist indentation or wear. The water quenched sample had hardness (615HB) which falls within the required hardness range and from the 0mm (surface) to 15mm, there was constant hardness recorded which indicates good hardenability leading to slow wear of the ore grinding media. The hardness of the oil quenched sample had low hardness (490HB) record which will lead to faster wearing out of the ore grinding media. Comparing the three samples using the graph the hardness of the water quenched is preferred to the other two samples, because of the hardenability characteristic shown on the graph.
Graph 1. Showing hardness (HB) against Depth from surface (mm) of 50mm steel ball.

Graph 2. Showing Hardness (HB) against Depth from surface (mm) of 80mm steel ball
From graph 2 above, the water quenched sample had hardness (660HB) with moderate slope from 0mm to 5mm. The hardness of the ore grinding ball as received was 645HB with constant hardness from 0mm to 5mm and steep slope to the end. For the oil quenched ball, 593HB was recorded at the surface showing low hardness per standard which 600 to 650HB. Comparing the three samples from the graph, the water quenched sample after heat treatment is preferred to the oil quenched and as received samples.

Graph 3. Showing Hardness (HB) against Depth from surface (mm) of 100mm steel ball

Graph 3 above shows hardness of water quenched sample, oil quenched sample and as received sample against depth from surface. These samples which were quenched in water had 659HB recorded as the hardness from the surface (0mm) and was constant through to 5mm which depicts that it has good hardenability thereby reducing the rate of wear that will occur which also applies to the as received sample and the oil quenched sample. This results, shows that using water as the quenching media
produce steel balls with good hardness and again when the tempering temperature is also reduced to 160°C.

DISCUSSIONS

Alloying elements present in steel have much effect on the mechanical properties when in operation as a whole. High carbon content increases hardness and wear resistance. The carbon content of steels is kept between 0.6 to 0.7 percent. Also, the Cr content should not be less than 0.5% in order to ensure a minimum hardness gradient. From the results showing the chemical compositions of the 100mm, 80mm and 50mm, it was observed that all the elements and its composition was in range when compared to the standard. The composition of Fe is balanced with only incidental impurities, such as sulphur (S) and phosphorus (P). Mn is added to supplement the Cr content, particularly in balls of larger diameter. Also it improves hot ductility and acts as austenite stabilizer. Copper (Cu) aids to improve formability, enhances corrosion resistance to certain acids and also promote an austenitic microstructure. Nickel (Ni) also in addition promotes an austenitic microstructure, increases ductility and toughness of the steel balls. Vanadium (V) increases the hardness of martensitic steels due to its effect on the type of carbide present in the steel. Molybdenum (Mo) increases the hardness at high tempering temperature due its effect on carbide precipitation. Titanium (Ti) is a strong ferrite and carbide former, increases mechanical properties at high temperatures. Cobalt (Co) increases hardness and tempering resistance, especially at high temperatures.

From the results of the microstructure analysis, it was observed that at the core of the 50mm ball there was presence of retained austenite as a result of delay in austenite transforming into martensite and tempered martensite which resulted in
decomposition of austenite into a mixture of cementite and ferrite as a result of tempering at high temperatures. The retained austenite present can cause damage during high impact conditions in the mill. Furthermore, the micrograph taken from the surface also had tempered martensite and cementite, because cementite is hard and brittle if it forms on the surface of the steel balls, rapid wearing rate occurs leading to early failure of the balls. From micrograph of ball 80mm, it was observed that at the core coarse pearlite which has inferior hardness, that is, low hardness and martensite as a result of cooling austenite rapidly from high temperatures were present. And there was presence of martensite at the surface. Although the martensite gave good surface hardness, as soon as the surface wears of it leads to the ball failing because of the low hardness of the core. Also from micrograph of 100mm ball sample there was a presence of tempered martensite with retained austenite and martensite for the micrograph taken from the surface.
CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.1 CONCLUSION

Although, chemical composition determines the mechanical properties of the steel balls as high carbon content increases hardness and wear resistance. The carbon content of steels are kept between 0.6 to 0.7 percent. Also, the Cr content should not be less than 0.5% in order to ensure a minimum hardness gradient (Tabrett, C.P., Sare, I.R., and Ghomashchi, 1996), heat treatment plays a vital role in determining the quality of the balls. Moreover, the quality of steel balls are influenced by the method through which the balls are produced. Due to impact and abrasion the balls are subjected to during the milling process, the steels are produced in such a way that they possess very high hardness in order to withstand these impact. However, the problem the mining companies faces with the locally manufactured balls is mostly the wearing off of the balls because of low hardness. As the heating time was increased and the tempering time decreased, moderate hardness was achieved.

Also, as the tempering temperature was reduced, the hardness gradient also reduced from the surface of the sample which will lead to low wear rate.
5.2 RECOMMENDATIONS

The heating temperature should correspond to the carbon content to obtain fully austenized steel ball for rapid cooling to the martensitic region.

In addition this report recommends, decreasing the tempering time of the balls during heat treatment and also choosing the appropriate heating time based on the size and thickness of the ball sample.
REFERENCES:


5. Van de Vijfeijken, Maarten (October 2010). "Mills and GMDs" (PDF). International Mining; 30.


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APPENDIX

A. HEAT TREATMENT

From Table 1 and 2, shows heat treatment process performed on the 100mm, 80mm and 50mm cut steel ball samples.

Table 1 showing the heat treatment performed on sample A (100mm 80mm and 50mm) quenched in water

<table>
<thead>
<tr>
<th>Ball size sample (mm)</th>
<th>Heating Temperature (°C)</th>
<th>Heating time (mins)</th>
<th>Tempering temperature (°C)</th>
<th>Soaking time (mins)</th>
<th>Cooling</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>810</td>
<td>90</td>
<td>160</td>
<td>60</td>
<td>Air</td>
</tr>
<tr>
<td>80</td>
<td>810</td>
<td>60</td>
<td>160</td>
<td>50</td>
<td>Air</td>
</tr>
<tr>
<td>50</td>
<td>810</td>
<td>45</td>
<td>160</td>
<td>45</td>
<td>Air</td>
</tr>
</tbody>
</table>

Table 2 showing the heat treatment performed on sample B (100mm 80mm and 50mm) quenched in oil.

<table>
<thead>
<tr>
<th>Ball size sample (mm)</th>
<th>Heating Temperature (°C)</th>
<th>Heating time (mins)</th>
<th>Tempering temperature (°C)</th>
<th>Soaking time (mins)</th>
<th>Cooling</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>810</td>
<td>90</td>
<td>160</td>
<td>60</td>
<td>Air</td>
</tr>
<tr>
<td>80</td>
<td>810</td>
<td>60</td>
<td>160</td>
<td>50</td>
<td>Air</td>
</tr>
<tr>
<td>50</td>
<td>810</td>
<td>4</td>
<td>160</td>
<td>45</td>
<td>Air</td>
</tr>
</tbody>
</table>
### B CHEMICAL ANALYSIS

**Table 3 showing the results of chemical analysis performed on 50mm ball:**

<table>
<thead>
<tr>
<th></th>
<th>Fe</th>
<th>C</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Si</th>
<th>Cu</th>
<th>Ni</th>
<th>Cr</th>
<th>V</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>97.714</td>
<td>0.642</td>
<td>0.704</td>
<td>0.011</td>
<td>0.002</td>
<td>0.258</td>
<td>0.012</td>
<td>0.032</td>
<td>0.521</td>
<td>0.002</td>
</tr>
<tr>
<td>Mo</td>
<td>Ti</td>
<td>Al</td>
<td>Nb</td>
<td>Co</td>
<td>Sn</td>
<td>B</td>
<td>Pb</td>
<td>0.063</td>
<td>0.004</td>
<td>0.028</td>
</tr>
</tbody>
</table>

**BALL SIZE: 80MM**

**Table 5 showing the results of chemical analysis performed on 80mm ball:**

<table>
<thead>
<tr>
<th></th>
<th>Fe</th>
<th>C</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Si</th>
<th>Cu</th>
<th>Ni</th>
<th>Cr</th>
<th>V</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>96.835</td>
<td>0.625</td>
<td>0.851</td>
<td>0.052</td>
<td>0.037</td>
<td>0.391</td>
<td>0.271</td>
<td>0.110</td>
<td>0.692</td>
<td>0.002</td>
</tr>
<tr>
<td>Mo</td>
<td>Ti</td>
<td>Al</td>
<td>Nb</td>
<td>Co</td>
<td>Sn</td>
<td>B</td>
<td>Pb</td>
<td>0.082</td>
<td>0.002</td>
<td>0.014</td>
</tr>
</tbody>
</table>

**BALL SIZE: 100MM**

**Table 6 showing the results of chemical analysis performed on 100mm ball:**

<table>
<thead>
<tr>
<th></th>
<th>Fe</th>
<th>C</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Si</th>
<th>Cu</th>
<th>Ni</th>
<th>Cr</th>
<th>V</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>97.603</td>
<td>0.701</td>
<td>0.737</td>
<td>0.005</td>
<td>0.004</td>
<td>0.276</td>
<td>0.010</td>
<td>0.031</td>
<td>0.528</td>
<td>0.000</td>
</tr>
<tr>
<td>Mo</td>
<td>Ti</td>
<td>Al</td>
<td>Nb</td>
<td>Co</td>
<td>Sn</td>
<td>B</td>
<td>Pb</td>
<td>0.068</td>
<td>0.004</td>
<td>0.026</td>
</tr>
</tbody>
</table>
HARDNESS TEST

Sample Surface hardness test (Rockwell)

*Table 7 showing surface hardness test result of 100mm, 80mm and 50mm of cut sample grinding steel balls.*

<table>
<thead>
<tr>
<th>Ball size (mm)</th>
<th>Test results (HRC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>61.3</td>
</tr>
<tr>
<td>80</td>
<td>61</td>
</tr>
<tr>
<td>50</td>
<td>60.7</td>
</tr>
</tbody>
</table>

50MM STEEL BALL

*Table 8 showing hardness from surface to center test results of the 50mm steel balls*

<table>
<thead>
<tr>
<th>Cut sample</th>
<th>C₁</th>
<th>C₂</th>
<th>C₃</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth from the surface (mm)</td>
<td>12.5</td>
<td>7.5</td>
<td>4</td>
</tr>
<tr>
<td>Hardness (HB)</td>
<td>527.1</td>
<td>579.8</td>
<td>632.4</td>
</tr>
</tbody>
</table>

80MM STEEL BALL

*Table 9 showing distance from the surface to center hardness test results of 80mm steel balls*

<table>
<thead>
<tr>
<th>Cut sample</th>
<th>C₁</th>
<th>C₂</th>
<th>C₃</th>
<th>C₄</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth from the surface (mm)</td>
<td>20</td>
<td>10</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>Hardness (HRC)</td>
<td>579.8</td>
<td>632.4</td>
<td>649.9</td>
<td>655</td>
</tr>
</tbody>
</table>
### 100MM STEEL BALL

*Table 10 showing distance from the surface to center hardness test results of 100mm steel balls*

<table>
<thead>
<tr>
<th>Cut sample</th>
<th>C₁</th>
<th>C₂</th>
<th>C₃</th>
<th>C₄</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth from the surface (mm)</td>
<td>25</td>
<td>20</td>
<td>15</td>
<td>10</td>
</tr>
<tr>
<td>Hardness (HRC)</td>
<td>445.4</td>
<td>527</td>
<td>597.4</td>
<td>667.4</td>
</tr>
</tbody>
</table>

### HARDNESS TEST ON SAMPLES AFTER HEAT TREATMENT

*Table 11 showing results of recorded hardness on 50mm cut sample ball*

<table>
<thead>
<tr>
<th>Cut Sample</th>
<th>C₁</th>
<th>C₂</th>
<th>C₃</th>
<th>C₅</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth from surface (mm)</td>
<td>12.5</td>
<td>7.5</td>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td>Hardness (HB) (water quenched)</td>
<td>615</td>
<td>628</td>
<td>630</td>
<td>630</td>
</tr>
<tr>
<td>Hardness (HB) (oil quenched)</td>
<td>490</td>
<td>510</td>
<td>570</td>
<td>579</td>
</tr>
</tbody>
</table>
From table 12 above, shows the results of the hardness recorded using a hardness tester on 80mm samples A and B which was quenched in water and oil respectively.
Table 13 showing results of recorded hardness on 100mm cut sample

<table>
<thead>
<tr>
<th>Cut Sample</th>
<th>C 1</th>
<th>C 2</th>
<th>C 3</th>
<th>C 4</th>
<th>C 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth from surface (mm)</td>
<td>25</td>
<td>20</td>
<td>15</td>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td>Hardness (HB) (water quenched)</td>
<td>520</td>
<td>560</td>
<td>615</td>
<td>630</td>
<td>632</td>
</tr>
<tr>
<td>Hardness (HB) (oil quenched)</td>
<td>493</td>
<td>517</td>
<td>546</td>
<td>603</td>
<td>605</td>
</tr>
</tbody>
</table>