FAILURE ANALYSIS AND DEVELOPMENT OF HIGH WEAR RESISTANT LOCALLY- MANUFACTURED GOLD - MILL GRINDING PLATES

By

Oji Ochea EMMANUEL, (B.Eng) 2006

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Declaration

I declare that the work in this thesis entitled failure analysis and development of high wear resistant locally-manufactured gold-mill grinding plates has been carried out by me in the department of Metallurgical and Materials Engineering. The information derived from the literature has been duly acknowledged in the text and a list of references provided. No part of this thesis was previously presented for another degree or diploma at this or any other institution.

_____	_____	_____
Name of Student	Signature	Date

Approval

This project report/thesis entitled FAILURE ANALYSIS AND DEVELOPMENT OF HIGH WEAR RESISTANT LOCALLY-MANUFACTURED GOLD-MILL GRINDING PLATES by Oji Ochea EMMANUEL meets the regulations governing the award of the degree of Masters in Metallurgical and Materials Engineering of the Ahmadu Bello University and is approved for its contribution to knowledge and literary presentation.

Prof A. K. Oyinlola Chairman, Supervisory Committee	_____ Signature	_____ Date
Dr. G. B. Nyior Member, Supervisory Committee	_____ Signature	_____ Date
Member, Supervisory Committee	_____ Signature	_____ Date
Prof. S.A. Yaro Head of Department	_____ Signature	_____ Date
Prof. H. Z. Hassan Dean, School of Postgraduate Studies	_____ Signature	__ _____ Date

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Dedication

This research work is dedicated to God Almighty, who is the source of my inspiration, power and might. Also to the entire family of Mr Oji Ochea, in-laws, relatives and well-wishers.

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Abstract

The research work is centered on the failure analysis of the as-received locally produced grinding plates, development of high wear resistant grinding plates capable of grinding gold-bearing mineral deposit in Bagega village of Zamfara State. The work was carried out by evaluating the chemical compositions of the as-received grinding plate samples, the compositions of the gold-bearing mineral samples, the microstructures of the as- received and developed grinding plate samples, mechanical properties (impact strength, hardness values) and wear rate of the as-received and developed grinding plates using Optical Emission spectroscopy (OES), Energy Dispersive X-ray Fluoresce (ED-XRF), Metallurgical microscope, impact and hardness testing machine, and the grinding machine. The analysis showed that the as-received locally produced grinding plate samples were grey cast iron with pearlite structure as the major matrix together with few cementite structures, generally characterized by poor mechanical properties. This explained the wear resistance of the samples in supporting grinding of the charged mineral for a longer period thereby prompting the samples to wear and fracture quickly in service. The two locally developed white iron base grinding plate samples showed a remarkable improvement in mechanical properties and wear resistant ability with increase in grinding duration from thirty two to seventy five minutes due to the presence of alloying elements that are capable of promoting abrasive wear resistant in comparism with the as-received failed grinding plates.

CHAPTER ONE

1.0. Introduction

Failure analysis is the process of collecting and analyzing data to determine the cause or causes of failure in general. It is the process by which scientists, technologists, engineers and business analysts use to assess the failure mechanism of any component in service that failed. It is an important area in every manufacturing industry (Neville, 2011).

Due to one reason or the other, machine component often experiences one form of service failure- the consequences which could include death and financial losses. Legal ramifications have encouraged the development of effective failure analysis method. While the cost of failure analysis may exceed the value of the part damaged, in some instances the cost of service failures usually far exceeds the cost of failure analysis (Neville, 2011).

Machine components may fail either as a result of the environmental conditions they are exposed to or the kind of stresses they experience. Often a combination of both environmental and stress condition can cause failure. In essence, these components are designed to withstand both the environmental condition and the stress they will be subjected to in service so that they can serve optimally in life. The designing of a metallic component involves not only a specific elemental compositions, it involves also specific aspect of materials selection processes such as, machining process, heat treatment, experience and skills of the producers. The huge arrays of different metals that exist have unique physical and chemical properties; specific properties are incorporated into metallic components to make them more robust to environmental conditions (Thomas, *et al* 1999).

Failure studies can never be over-looked; investigation reveals that typical failure mode that involves various types of corrosion and mechanical damage in United State of America consumed up to twenty five percent of her Gross Domestic Product in 2009 (Neville, 2011).

Casting activities are done in our society by local artisans and technicians that cast different parts including cast iron grinding plate used domestically. Products of this nature go into the market (without proper certifications) often perform below expectation in service; sufficient effort has not been made to evaluate or to control these activities. Consumers have no choice other than to obtain the product since no substitute is available and if available may be very costly (Kwofie and Chander, 2012).

Some of these products especially the grinding plates are used by the domestic mineral processing industries. Due to lack of standardization and other related factors such as poor material selections, low level of minimum education, substandard equipment, poor quality control and corresponding heat treatment operations can be part of the factors leading to their early failure in service. There is need therefore for a total appraisal of the production process in order to meet economical expectations and to reduce failure (Kwofie and Chander, 2012).

1.1. Background of the Research

The outcome of any grinding process in service depends on the wear resistance of the abrasive plate, the nature of fracture and other failure mechanisms which play important role in determining the efficiency of the grinding process and to a large extends the quality of the work piece (Jackson, 2007). Wear is mechanically induced surface damage that results in progressive removal of material. Wear usually results in a loss of weight

and change of dimension over time. In severe situations, wear can result to fracture usually from surface originated fatigue crack (Dieter and Schmid, 2013). Wear typically occurs when two solid materials are in close contact with each other, either in sliding or rotational motion. The wear of a material is closely associated with the friction of the sliding surfaces and its degree of damage is strongly influenced by the presence of a lubricant.

Whether performed in a large or small scale generally, mineral grinding is quite often an integral part of an industrial process in mineral processing industries. In most cases the grinding mill may be the single most costly item for the production operation. Installing a grinding mill which is suitable for the purpose would be one of the main requirements for cost effective and trouble free mineral processing (Normal and Decker, 2010). Every processing plant has its peculiar problem(s) based on the nature of work; failure can never be ruled out.

1.2. Statement of Research Problem

The increasing demand for the maximization of output, improvement on indigenous industries through failure reduction stimulated the passion towards the failure analysis of the Bagega mineral processing plant in Anka local government area of Zamfara State, which experienced rapid failure in grinding operation of the gold-bearing mineral deposits that exist in large quantity. Based on preliminary investigation, the as-received grooved cast iron grinding plates experience failure when used for grinding the gold-bearing minerals. The occurrence of this failure called for immediate plate replacement for grinding operation to continue. Also, from the previous history of the processing operation, the grinding plates last within a period of thirty two minutes in the course of

processing a specific type of gold-bearing mineral, while with different deposit of gold-bearing mineral, the grinding plate will last for an average period of thirty eight minutes before failure occurs. This rapid rate of failure poses high challenge to the mineral processors in terms of economic aspect in replacing the worn out plates. Presently the mill in Bagega mineral processing company falls under attrition mill group (Normal and Decker 2010; Gupta, 2003).

1.3. Justification

Through this work, the appropriate technology for the development of high wear resistant grinding plates for grinding the Bagega gold-bearing mineral will be developed. Also, the processing of the Bagega gold-bearing mineral will be enhanced thereby increasing job opportunity for the teaming population of the Nigerian youths.

1.4. Aims and Objectives

1.4.1. Aim

The aim of this work is to analyze the failure mode of Bagega gold mill grinding plates and development of high wear resistant locally manufactured gold mill grinding plates that can support grinding for a longer period.

1.4.2. The specific objectives are:

1. The determination of the failure mode of the as-received grinding plates of Bagega gold-bearing mineral grinding mill by evaluating their wear resistance.

2. Determination of the chemical compositions of the as – received grinding plates using Optical Emission Spectroscopic machine (OES).

3. Developed grinding plates to withstand the grinding conditions of the Bagega gold-bearing mineral samples.

4. Determination of the mechanical properties (hardness, wear resistant and impact strength) of the as-received and developed grinding plates.

5. Determination of the microstructure of the as–received and the developed grinding plate using Metallurgical Optical Microscope (MOM).

6. Determination of the chemical compositions of the Bagega gold-bearing mineral deposit using Energy Dispersive X-ray Fluoresce (ED – XRF) machine

1.5. The Scope of the Work

The research work will involve the following areas, evaluation of the mechanical properties (hardness and impact properties) and wear rate of the as-received grinding plate samples, development of new grinding plates and assessment of their mechanical properties (hardness values and impact values), their wear rate determination, analyzing the chemical composition of the as-received grinding plates, chemical compositions of the gold-bearing mineral samples, determination of the work index of the gold-bearing minerals, determination of the microstructures of the as-received and developed grinding plates.

CHAPTER TWO

2.0. Literature Review

2.1. Failure Analysis Overview

It has been established that more than fifty percent of failure associated problems in mineral processing plant occurred in the crushing and grinding units - an area with limited lubrication possibilities (Jackson, 2007). The grinding unit is the most singular factor that determines cost of production due to high cost of maintainace involved (Jackson, 2007).

The general procedure for conducting a sound failure analysis is similar for metallic and non- metallic component (Colangelo and Heiser, 1987; Myer, 2002). The steps include information gathering, visual examination, photographs, eye witness reports, preservation of failed parts, non-destructive and destructive testing analyses, characterization of the material properties (which includes chemical, mechanical and thermal properties), selection, preservation and cleaning of fracture surface, macroscopic examination of fracture surface, secondary cracking and surface condition, microscopic examination, selection preparation of cross section, identification of failure mechanism, fracture mechanism analysis, attempt to reconstruct the failure scenario, testing to simulate failure, data review, formulation of conclusion and reporting.

Although, the basic steps of failure analysis are nearly identical, some differences exist between metals and plastics. Non destructive testing like magnetic particle inspection, eddy current and radiographic inspection methods are not generally applied to plastics for obvious reasons. However, ultrasonic and acoustic emission techniques find application for both materials (Colangelo and Heiser, 1987; Myer, 2002).

Similarly, different chemical test methods are necessary; typical test methods for metals are optical emission spectroscopy, inductively coupled plasma and combustion. Fourier transformation infrared spectroscopy is used extensively to identify plastics by molecular bonding, thermal testing, differential scanning calorimetry are also very important for polymer characterization (Colangelo and Heiser , 1987). Energy dispersive X-ray spectroscopy where used in conjunction with the electron scanning tunneling microscope (ESTM), is a very good tool for both metals and plastics. Also, different chemical solutions are required for metals and plastics to clean, protect fracture surfaces and etch cross section so as to reveal the microstructure (Colangelo and Heiser, 1987).

2.2. Causes of Failure

The primary objective of a material failure analysis is to determine the root cause of failure whether it is metallic or non metallic materials, identify the best solution and redesign the product to prevent or minimize future failures. Ideally the root cause of failure can be assigned to any of these three categories such as manufacturing, service or material selection (Colangelo and Heiser, 1987, Myer, 2002). Often, several adverse conditions contribute to the part failure. Some of these causes are common to both metals and non metals, they include improper material selection, overly high stresses and stress concentration are examples of design related problems that can lead to premature failure (Neville, 2011).

Materials selection must take into account of environmental sensitivities as well as requisite mechanical properties in addition to the welding/joining characteristics. Stress raisers are frequently a preferred site for fracture origin, particularly in fatigue. Stress

raisers include thread root, sharp radii of curvatures, through holes, and surface discontinuities. Such as gate marks in molded plastics parts (Gilder, 1960).

Many manufacturing and material problems found in metals are observed to have a corollary in plastics. Weld areas are trouble prone area for metals just like knit lines in molded plastics. High residual stresses can result from metal forming; heat treatment, welding and machining often contribute to failure. Porosity and void common to metal castings and plastics molded parts serve as stress raisers which reduce load carrying capacity of the material.

Other manufacturing and materials related problems that may lead to failure include adverse thermo mechanical history, poor microstructure, material defects, contaminations by chemicals, excessive wear rate, impact force, overloading and electrical discharge (Kwofie and Chander, 2012).

2.3. Wear Mechanisms as Agent of Failure

Wear occurs as a natural consequence when two surfaces with a relative motion interact with each other (Halling, 1987). It can also be explained as the progressive loss of substance from the surface of a body brought about by mechanical action (Halling, 1987). It has been established by Halling, that a better understanding of wear can be acquired by recognizing the several distinct and independent mechanisms that are involved. Based on an elaborate survey (Halling, 1987; Myer, 2002), four distinct mechanisms such as

adhesive wear, abrasive wear, corrosive wear and surface fatigue have been categorized as possible forms of wear. Additional mechanisms involving erosion cavitation and impact chipping being captioned under the heading of ‘Minor Types of Wear’ has been classified as the fifth form of wear mechanism (Halling, 1987).

2.3.1. Adhesive wear

Macroscopically, smooth surface are rough on an atomic scale (Halling, 1987; Myer, 2002). When two of such surfaces are brought together, contact is made at relatively few isolated asperities (angles). When a normal load is applied, the local pressure at the angle (asperities) becomes extremely high. The yield point stress is exceeded and the asperities deform plastically, until the real contact area has increased sufficiently to support the applied load (Halling, 1987).

In the absence of surface films the surface would adhere together, but a small amount of contaminant prevent adhesion under purely normal loading. However, relative tangential motion at the interface acts to disperse the contaminant films at the points of contact, in order for cold welding of the junctions to take place while further continuous sliding causes the junction to be sheared, thus leading to the formation of new junction. According to Halling, this model also leads naturally to the formulation of a mechanism of wear, but not to a precise quantitative law of wear. The amount of wear depends on the position at which the junction is sheared. If shear takes place at the interface then wear is zero, if shear takes place away from the interface then metal is transferred from one surface to another, material is detached to form loose wear particles. The transfer of material from one surface to another by adhesion has equally been studied by several

investigators, (Kerridge and Lancester) as reported by Halling. They used a radioactive pin of 60: 40 brass, rubbing against a ring of tool steel; the transfer of material was demonstrated by placing a photographic film in contact with the tool steel after rubbing and obtained an autoradiograph of the transferred brass from the wear track.

2.3.2. Abrasive wear

In the case of abrasive wear, the wear particles are removed from the surface by the plowing and gouging action of the asperities of a harder mating surface or hard particles trapped between the rubbing surfaces. This type of wear is manifested by a system of surface grooves and scratches, often called scoring. The abrasive wear condition in which the hard asperities of one surface wear away the mating surface is called two-body wear and the condition in which hard abrasive particles between the two surfaces cause the wear is called three-body wear (Myer, 2002).

The term ‘abrasive wear’ covers two types of situation according to Halling. In both cases wear is occasioned by the removal of softer material by a harder surface. In the first instance a rough hard surface slides against a softer surface. Under the second situation abrasion is caused by loose hard particles sliding between rubbing surfaces. The action of a film or emery paper against a softer metal is an example of the first type of abrasion. For the occurrence of abrasive type of wear it will require that one surface must be harder than the other contacting surface; also the surfaces must be rough. The second mechanism is still of great importance. Not only do most mechanisms work in an environment containing much airborne dust and dirt, but also the products of corrosive wear are more often than not abrasive in character. Particles of hard metal produced by the adhesive wear mechanism can also cause abrasion. However, airborne dust and grit is the largest source of abrasive particles and the practical solution is to exclude the dust by adequate sealing and filtration (Halling, 1987).

The fact that dust from atmosphere is a major cause of abrasive wear probably explains the large variability in wear measurement (Halling, 1987). Thus, where attempts are being

made to measure wear due to causes other than abrasion, Cattaneo and Starkman (Halling, 1987) have suggested that the average wear rates obtained are more appropriate than lowest values. Both researchers suggested that increase from the minimum value was due to insufficient precautions against ingress of abrasive particles. In order to obtain a quantitative expression for abrasive wear, a simplified model, in which one surface consists of an array of hard conical asperities (contact angle), of semi angle θ is being assumed. The second surface is softer and flat, as an example a single asperity creating a track through the softer surface is shown in the figure 2.1 (Halling, 1987).

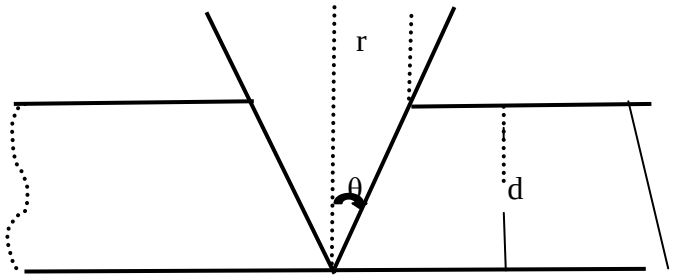


Figure 2.1: Abrasive wear by a conical indenter (Halling, 1987).

In traversing a unit distance d, the asperity displaces a volume of material rd. But,

$d = r\cot\theta$. (2.1)

Therefore, the volume D, displaced by one asperity in unit distance can be expressed as

$D = r^2\cot\theta$ (2.2)

where r = the radius of conical indenter and θ = the angle of contact. Assuming the material has yielded under the normal load and therefore the asperity supports a load w,

$w = \pi r^2 Po/2$, (2.3)

where Po is the yield pressure of the softer material. If there are n asperity contacts, the total normal load W.

$W = n\pi r^2 \mathrm{Po}/2$ (2.4)

And the volume displaced per unit distance Q, is express as

$Q = nr^2 \cot\theta$. (2.5)

Eliminating n, the equation becomes,

$Q = 2W\cot\theta / \pi Po$. (2.6)

According to Halling (1987), in derivation of this equation, no account of the distribution of asperity height and shapes has been taken. However, an equation of the form

Q= KaW/H, (2.7)

Where Q is the total volume displaced in a unit distance, Ka is the abrasive wear constant, H is the hardness of the softer material and W is the normal load. This equation 2.7 is found to cover a wide range of abrasive situations. As wear due to abrasion proceeds, some blunting of the hard asperities or particles will occur, thus reducing the rate of wear. However, an abrasive grit, which is brittle, can fracture causing a resharpening of the edges of the particles and an increase in wear rate (Halling, 1987).

Many investigators have confirmed that hardness is the most important parameter in abrasive wear resistance (Myer, 2002; Halling, 1987; Gilder, 1960). In selecting materials for abrasive wear resistance, therefore, it has been established that both hardness and modulus of elasticity are key parameters (Myer, 2002). Increasing wear resistance is associated with higher hardness and lower modulus of elasticity since both the amount of elastic deformation and the amount of elastic energy that can be stored at the surface are increased by higher hardness and lower modulus of elasticity (Myer, 2002). Kruschov, plotted resistance to wear against hardness for a range of annealed pure metals, obtaining

a linear relationship (Halling, 1987), also found that prior work hardening of the pure metals had no effect on the wear rate. These and other experiments have led to the conclusion that during abrasion, a metal surface work hardens to a maximum value and it is this value of hardness which is appropriate when considering abrasion resistance (Halling, 1987). Also three laws of abrasion were deduced by Holm, Burwell and Strang according to Halling (1987). They stated that, the volume of wear material is proportional to the distance of travel. Also the volume of wear material is inversely proportional to the yield stress, or the hardness of the material and the volume of wear material are proportional to the load (Halling, 1987).

2.4. Failure Induced by Ore Hardness Values

Starkey and David, (2008) established that failure of the grinding media could equally come from the hardness of the ore. Since there is no effective way to determine the workload of the media, an increasing number of investigators and designers do accept that a representative hardness distribution function for an ore body is required for the best design of grinding media (Starkey and David, 2008). Previously, representative samples for pilot plant testing were considered to be the norm. But if the depth of ore bodies and the requirements to test minus 200 mm of ore samples sieve size were considered, it is immediately clear that either a great deal of money will be spent to get the samples or the sample tested will not be representative. The latter condition is one of the causes of failure in Semi Autogenous Mill (SAG) and Autogenous mill (AG) grinding circuit (Starkey and David, 2008). According to Starkey, (2008) once the representative hardness distribution function has been defined, maximum power to grind the hardest ore to a selected sieve size could be determined.

2.5. Mills used for Grinding

Grinding mill or grinders that are used for mineral processing can be broadly categorized into two groups namely intermediate/fine grinders and ultrafine grinders (Normal and Decker 2010; Gupta, 2003).

Intermediate and fine grinders include low speed tumbling mill, rolling- compression mills and attrition mill (traditional mill) (Normal and Decker 2010; Gupta, 2003).

Low speed tumbling mill which can also be called rotating or revolving mills consists of a large diameter, short length cylinder fitted with lifting bars. The rotating speed is usually low about eighty percent of critical speed (Which is the speed at which the charge will be pinned to the rotating drum). This type of mill is suitable for mineral that are coarse in nature; once it is broken, it will disintegrate readily into small sizes. Examples of the mills include autogenous mill, semi autogenous mill, rod mill, ball mill, pebble mill, tube mill (Normal and Decker, 2010; Gupta, 2003).

Rolling-compression mill: This group of mill is used for dry grinding only and accepts only relatively soft minerals such as coal and limestone. Size reduction is by compression between the balls and race compared to impact method used in rotating mills. Feed sizes vary according to the machines (Normal and Decker, 2010; Gupta, 2003).

Ultrafine grinders are high speed mill whose product is very fine to the extent that material may not require regrinding. Included in this group of mill are hammer mill, pin mill, turbo mill, fluid energy mill and stirred media mill (Normal and Decker, 2010; Gupta, 2003). The attrition mill (traditional mill) is the most common type of mill found in the developing countries. The output of such mill is low and it is usually used for small scale milling operations to generate fine products. Included in this type of mill are plate mill, chilean edge mill, stamp mill, horse mill, wind mill, pestle and mortar type of mill.

Over the years some of these mills have changed only a little in their design (Normal and Decker, 2010; Gupta, 2003).

The attrition mill works on the principles that two cast iron circular disc plates with grooved surfaces are used for grinding (Normal and Decker, 2010; Gupta, 2003). It compresses the charged materials in the grinding media with high speed of revolution in order to reduce the ore to powder form.

2.6. Minimization of Failure through Wear Reduction

The findings of Broeckmann and Andrew (2005) reported that wear by the abrasive particles can be minimized effectively by the presence of hard phases like carbides, borides or nitride in the tool or work piece. Requirements for the distribution of these phases are different based on shapes, sizes applications and environments.

Incorporation of material through design that promote hard phase is a good step in enhancing wear life. Also combination of grinding parameters such as equivalent chip thickness and grindability of the work piece determines the dynamic plate hardness. No single feature of the grinding process can be used to predict fracture and wear pattern in advance (Broackmann and Andrew, 2005). The difficulty involved when relating grinding plate wear due to fracture to a particular grinding condition arouse from bulk of knowledge about the load applied to both abrasive media and their response to the applied load (Jackson, 2007).

Jackson (2007) suggested that wear measurement should be based on reduction of the grinding wheel diameter, which was attributed to abrasive wear rate. The strongest evidence in support of the idea of fracture due to mechanical loading is that fracture

occurs some distance away from the cutting edge. Effort in reducing failure positively was achieved by design (Jackson, 2007).

2.7. Materials used for Grinding Mineral Ores

Grinding machine plates should be able to provide high mechanical strength that can trench the solid matter charged in the grinding media by overcoming the strength of interior bonding forces of the solid matter as has been stated by Gardula, Laird and Robert (Broeckmann and Gardula, 2005). Machine grinding component that can be able to perform such work must possess hard phases distributed in soft tissue matrix, excellent wear resistance, high hardness, high damping capabilities so that it can provide the desired characteristics needed for grinding. Cast iron and its alloys possess these qualities when compared with other materials (Gilder, 1960; Laird, 1991; Robert, 2011). There are different types of cast iron such as ductile, malleable, grey and white cast irons.

Within these types of cast irons, high alloy and white iron are primarily used for abrasion resistant applications and are readily cast into parts needed in machinery for crushing, grinding and handling of abrasive materials (Laird, 1991; Robert, 2011).

The high alloy white cast irons fall into three major groups which are nickel-chromium, chromium- molybdenum and high chromium white iron with their chemical composition are appended in table 2a, 2b and 2c respectively (Laird, 1991; Robert, 2011; Gilder, 1960).

Table 2a: Chemical composition of low nickel – chromium white iron.

Element	**C**	**Ni**	**Cr**	**Mo**	**Si**	**Mn**	**P**	**S**
Percentage	3.0-3.6	3.0-5.0	1.0-4.0	1.0-4.0	0.3-0.5	0.3-0.7	0.1-0.3	0.15 max

Table 2b: Chemical composition of chromium – molybdenum white iron.

Element	C	Ni	Cr	Mo	Si	Mn	P	S
Percentage	3.0-3.6	3.0-3.6	11-23	0.5-4.0	-	0.8-1.3	.01-.06	0.1 max

Table 2c: Chemical composition of high chromium white iron.

Element	C	Ni	Cr	Mo	Si	Mn	P	Cu
Percentage	3.0-3.4	1.0	23-28	1.0-1.5	-	-	-	1.0

The major groups of white iron are mainly used for the development of wear resistance materials. However, high chromium white iron can be used as corrosion resistance materials. The large volume fraction of primary and/or eutectic carbides in their microstructures provides the hardness needed for crushing and grinding other materials. The metallic matrix supporting the carbide phase in this iron can be adjusted by alloy content and heat treatment to develop the proper balance between the resistance to abrasion and the toughness needed to withstand repeated impact loading (Laird, 1991; Robert, 2011; Gilder, 1960; Jackson, 2007).

Also, wear resistant steel with high manganese content can be used for mineral grinding (Marshall, 2007). This type of steel is fully austenized, quenched, non-magnetic, with exceptional high level of wear resistance when subjected to high impact pressure or surface contact in service. Production of this steel according to international standard leads to increase in hardness from 200 HBN in as delivered plates to 600 HBN in service.

For a long period in service, the hardness also increases due to work hardening (Marshall, 2007). The chemical compositions and the mechanical properties of manganese steel component are given in tables 2d and 2e respectively.

Table 2d: Composition of manganese steel used for wear resistance application.

Element	Carbon	Silicon	Manganese	Sulphur	Phosphorus
Percentage	1.13	0.40	13	0.003	< = 0.20

Tables 2e: Mechanical properties of manganese steel for wear resistance application.

	Hardness Value (HBN)	Yield Strength (MPa)	UTS (MPa)	EI %
Typical values	220	380	940	40
Guaranteed values	180 -245	350	800	30

2.8. Carbon Equivalent Value (C.E.V)

Generally, cast iron specification may solidify to form grey, white or mottled depending mainly upon the eutectic value and the rate of cooling as reported by previous findings (Sighn, 2012 FOSECO, 1994; Kwofie and Chander, 2012). Thus, eutectic value is a factor of the composition of iron. (FOSECO, 1994; Kwofie and Chander, 2012). The simplest form used for evaluating the composition of an iron is the carbon equivalent value (C.E.V), expressed as (Kwofie, 2012):

C.E.V = %Total of carbon + 1/3(% Silicon + % phosphorous) (2.8)

The C.E.V determines how close a given composition of iron is to the theoretical iron carbon eutectic point and therefore, how much free graphite is likely to be present for a given cooling rate. The carbon equivalent value also tells immediately whether cast iron

specification is hypoeutectic, eutectic or hypereutectic and by how much, using a standard eutectic value for plain iron of 4.3 %C (Kwofie, 2012). It is used as an index to convert the amount of silicon and phosphorous into equivalent amount of carbon. It is this C.E.V rather than the actual carbon content which applies with commercial irons when using the iron graphite and iron cementite phase diagram (FOSECO, 1994; Kwofie, 2012). For a given cooling rate, carbon equivalent value determines how close an iron specification is to the eutectic point.

Generally, the lower the carbon equivalent value, the greater is the tendency for a molten cast iron specification to solidify as white or mottled cast iron. Therefore, carbon equivalent is a useful guide to detect the tendency of a solidifying cast iron to form white iron; this is favoured by low silicon content which lowers the C.E.V below the eutectic value, but pouring temperature and cooling rate also have marked influence on the resulting microstructure (Davies and Oelamann, 1984).

2.9. Effect of Some Alloying Elements in Cast iron

When desirable martensitic structure, austenitic structure and improvement in wear and corrosion resistance are needed, alloying elements can be added to cast iron (Higgins, 1993; Robert, 2012; Sighn, 2012). The addition helps to impart the desired properties in the substance and also to increase the hardness of cast iron by stabilizing cementite and forming other harder carbide (Gilder, 1960; Higgins, 1993, Sighn 2012).

Carbon content determines both the relative amounts of carbides and the hardness for a given matrix structure by forming eutectic carbide (Higgins, 1993; Robert, 2011). Lower carbon content gives more primary dendrites at the expense of the carbide content. This results in a lower hardness and abrasion resistance but higher toughness. By changing the

carbon content, test resistance to abrasion and fracture can be acquired according to the application.

Nickel is added to obtain a matrix structure without or less pearlite and to refine the grain. The necessary nickel content depends on the cooling rate, the more the nickel, the more support it gives to produce suppress pearlite formation and more abrasion resistance to the component. At lower nickel, hardenability is not enough to suppress pearlite formation, resulting in reduced hardness, wear and abrasion resistance. Also, excessive nickel content will favour the formation of retained austenite, which lowers the hardness by promoting graphitization (Higgins, 1993; Robert, 2011; Sighn, 2012).

Molybdenum is added to increase hardenability of cast iron in reasonable amount and inhibit the formation of pearlite (Laird, 1991; Gilder, 1960; Higgins, 1993; Robert, 2011; Sighn 2012).

It dissolves in the ferrite, but in larger amount forms double carbides. It promotes uniformity of the microstructure and increases the impact value of the component.

Chromium is a strong carbide stabilizer, and so inhibits the formation of graphite and increases hardenability. Moreover, the carbides formed by chromium are more stable and less likely to graphitize under the application of heat than the iron carbide. Irons containing chromium are therefore less susceptible to growth. Using both chromium and nickel together in cast iron in the ratio of two to three parts respectively, overcome the disadvantage of using one (Laird, 1991; Gilder 1960; Higgins, 1993; Robert, 2011; Sighn 2012).

CHAPTER THREE

3.0. MATERIALS, EQUIPMENT AND GENERAL EXPERIMENTAL PROCEDURES

3.1. Materials

The materials used in this research work include the mineral samples, as-received grinding plate

samples, ferrochrome, nickel pellets**,** ferromolybdenum and grey iron scraps.

3.2. Equipment

Table 3.1: Equipment used for the analysis

S/No	Type of Equipment	Location of the Equipment	Manufacturer	Quantity
1	Brinell hardness machine	Metallurgical and Materials Eng. Lab. ABU	Brooks Ind Ltd, Uk.Model CRBD	1
2	Impact testing machine	Mechanical Engineering Lab. ABU	Hoopman Ind Ltd, Uk.	1
3	Rotary Furnace	Artillery Barracks, Kaduna	Artillery Tech, Nig. Ltd	1
4	Grinding & polishing Machine	Metallurgical and Materials Eng. Lab. ABU	John Halt Ltd, Uk	2
5	Metallurgical Microscope	Metallurgical and Materials Eng. Lab. ABU	Benhosre Intl, Germany.	2
6	Energy Dispersive X-ray Flourence machine (ED-XRF)	NMDC, Jos, Plateau state.	Light house Ind. Ltd, Uk.	1
7	Optical Emmision Spectroscopic	DICON, Kaduna, Kaduna State.	Cophen Ind. Ltd,USA,	2

	machine			
8	Electronic Weighing balance	Bagega Mineral Industries.	Bruce Ind, Ltd, Uk.	1
9	Attrition grinding Machine	Bagega Mineral Industries	Deniver group of Coy, Germany, Model A1	1
10	Lab. Jaw Crusher serial No. BDA 15571	NMDC, Jos, Plateau state.	Joy, Manufacturing Co. Uk.	1
11	Cone Crusher serial No. 003	NMDC, Jos, Plateau state.	Deniver Equip.Co. Uk	1
12	Rolling Crusher serial No. B7141	NMDC, Jos, Plateau state.	Deniver Equip.Co. Uk	1
13	Ball Milling machine, serial No.69012	NMDC, Jos, Plateau state	Sprecher & Schuh Ind. Control, USA.	1
14	Automatic sieving machine	NMDC, Jos, Plateau state	Deniver Endecote Industries USA.	1

3.3.0. Methodology

3.3.1. Determination of the hardness of the as-received and developed samples

Hardness values of the samples were determined using Brinnel hardness testing machine located in the Department of Metallurgical and Materials Engineering at Ahmadu Bello University, Zaria. The machine is equipped with a diamond cone indenter of diameter 2.5 mm, with a facility of applied minor load 10kg and major load of 187.5kg. The test pieces of 10 cm length originally cut from each cast plates and the as - received plates were further machined to obtain small pieces of dimension 2 cm by 2 cm by 2 cm (cubic shape) that were mounted on a holder. The mounted piece, which provides good balancing on the hardness tester specimen stand, was then ground on silicon carbide abrasive paper of 200. 300 grits to obtain a flat surface to ensure good positioning of the diamond cone

indenter for the test to be conducted according to ASTM E18 hardness testing specification.

Before the hardness of the mineral samples were taken, the surfaces of the mineral samples were prepared with diamond tool cutter, to obtain smooth flat surface that can be mounted on the machine to conduct the test.

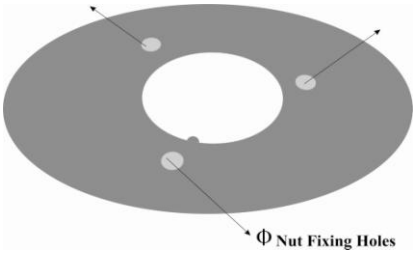
3.3.2. Determination of the impact strength of the as-received and developed samples

The impact test was carried out using Izod Avery Denison impact testing machine at the Department of Mechanical Engineering, Ahmadu Bello University, Zaria. This was done according to ASTM E5 impact testing specification. When the machine was zeroed, each test bar was gripped vertically in a vice and a force needed to break it was released from the pendulum through an angle that corresponded with the absorbed energy (joules) in breaking each sample. Also, the impact the impact strength of the mineral samples were determined by cutting a sizable portion of the mineral samples with a diamond tool cutter to obtain the impact requirement size for the analysis.

3.3.3. The development of new high wear resistant grinding plates

Grey iron scraps were melted in the fuel fired rotary furnace at the Artillery Barrack Foundry Workshop, Kaduna in Kaduna State. The furnace was charged three quarter filled to allow space for its rotation and subsequent mixing of the charge during melting. Prior to the pouring temperature of 1440 ^{o}C, the ferro alloys such as ferrochrome, ferromolybdenum and nickel were added according to the composition given in Table 2 of Appendix III. These elements had been adjudged to promote hardness and wear resistance of a material (Laird, 1991; Gilder 1960; Higgins, 1993; Robert, 2011; Sighn, 2012).

The choice of this material in Table 2 of Appendix III was made according to the ASTM 532, a standard for enhancing the service condition of the as-received samples. The cast samples were of circular disc in shape with grooves, surface area of 531 cm^2, thickness of 1.1 cm, hollow circular space of area 95 cm^2 with three small holes of 2 cm for nut fixing as shown in the plate 3.1 and schematically shown in Figure 3.1. Table 3.2 shows the chemical compositions of the developed samples C and D analyzed with Optical Emission Spectroscopic machine after production.



, ϕ = 2cm.

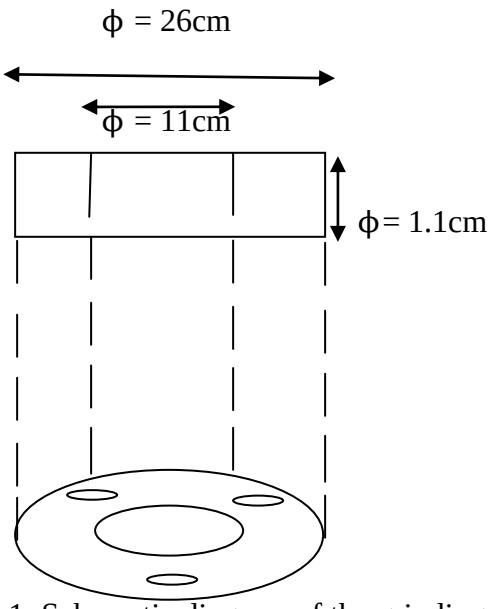


Plate 3.1: Picture of grinding plate. Figure 3.1: Schematic diagram of the grinding plate.

Taking the volume of the cast plate to be area multiplied by thickness minus area multiplied by minor hollow space in the plate, the volume of the plate was determined from the expression of the form.

$$V = \pi R^2 * \mathrm{D} - \pi r^2 * \mathrm{D} \qquad (3.1)$$

Where V= volume of the plate, R= external Radius, r =internal radius of the plate and D = the thickness of the plate. From the above stated dimensions, V = 531*1.1 – 95 *1.1 =

479.6 cm^3 volume of the plate, density of iron is 7.5g/cm^3, the mass of the plate can be calculated by multiplying volume and density. Also by direct measurement, the weight of the developed plate is 3.5 kg. Thus,

Mass = Density * Volume. (3.2)

Table 3.2: Chemical compositions of the developed sample C and D

Elements	C	Si	Mn	P	Ni	Cu	Ti	Mo	Co	Sn	V	Cr	Al	Fe
Sample C	3.122	0.6808	0.1785	0.075	3.1020	0.0642	0.007	0.0101	0.060	0.0178	0.0340	1.9250	0.001	Balance
Sample D	3.105	0.5810	0.1961	0.053	3.1140	0.0601	0.021	0.6902	0.302	0.0174	0.0338	3.1542	0.009	Balance

3.3.4. Determination of wear rate of the plates

Wear rate values were determined by grinding the mineral sample with the as–received and developed grinding plates at the grinding mill. The procedure was to record the initial weight of the plates before mounting it on the machine and the starting time, work with the face until it was worn out. The time it lasted before it was worn out was recorded, the plates were removed and re-weighed, and the weight obtained was recorded as final weight. The same procedure was repeated with the other face of the plate and re-weighed, record the weights as final weights 2. The plate was resharpened (Regrooved) on both sides, the procedures were repeated to ascertain the weight loss progression. The weight loss was deduced by subtracting the final weight from the initial weight using the following expression:

$$W_l = W_b - W_f \quad (3.3)$$

where W_b is initial weight, W_f is the final weight and W_l is the weight loss (kg). The rate of wear (W_r) is deduced by dividing the weight loss in each face with the time (T) it lasted before it was worn out (Kwofie and Chander, 2012). That is;

$W_r = W_l/T.$ (3.4)

where T, is time (minutes) each face lasted. Record the total time each sample lasted during grinding within the testing period was recorded as the cumulative duration (C.T). The procedure is in accordance with the ASTM G65 of three body wear specification.

3.3.5. Microstructural assessment of the samples

A representative section of each sample was cut to obtain a sizeable piece that could be mounted. This was mounted with a Bakelite powder to allow easy handling of the mounted sample for subsequent grinding and polishing operations. The grinding was done mechanically on progressive grades of silicon carbide abrasive paper ranging from 240 to 600 grits sizes. Thereafter, the ground specimen was polished using alumina polishing paper suspended in distilled water and finally using 0.3 micro alumina powders to obtain a mirror surface.

After polishing, the test specimen was etched using 2 % Nital reagent, which consists of 2% Nitric acid (HNO_3) in ethyl alcohol to reveal the microstructure according to ASTM E3 standard guide for microstructural assessment. Finally the microstructure of each specimen was examined using metallurgical microscope with in-built camera and micrographs (photographs) produced at hundred magnifications were captured.

3.3.6. Characterization of the gold-bearing mineral

Based on random sampling method, mineral samples were collected from two different mining sites at Bagega Village in Anka Local Government of Zamfara State. Samples collection were done at various spot of about six to seven kilometers apart from these two mining site, twenty kilogramme of the two different gold-bearing minerals of interest were collected for analysis and further work. Also, a granite ore was collected as a

reference mineral which have a known work index from Furaka Village in Jos North Local Government Area, Plateau State, using the same procedure.

The gold-bearing minerals from Bagega Village were characterized to determine their chemical constituents using ED-XRF machine available at the National Metallurgical Development Centre Jos, Plateau State.

3.3.7. Characterization of the as-received plates

The as-received plates sample were characterized to determine its chemical compositions with Optical Emission Spectroscopic (OES) machine located at the Defense industries of Nigeria (DICON), Kaduna State.

3.3.8. Determination of the work index of the gold-bearing minerals

The work index for the two mineral samples was determined by using alternative modified Bond's method known as Berry and Bruce method (Oladunni, 2012; Gupta, 2003). This involves using a reference ore of known work index; in this research granite was used. Grinding the ores with same energy to a size of eighty percent passing size of 100 microns. Boulder ore samples were broken manually to obtain the acceptable size for laboratory jaw crushing operation followed by cone crushing and roll crushing; the product were pulverized using ball mill machine; part of the pulverized samples were then weighed for sieve analysis. This was carried out at the National Metallurgical Development Centre (NMDC), Jos. The modified Bond method of determining the network index of mineral involves the use of reference mineral of which its grindability is known. The procedures were as follows:

(i).100g each of samples of the mineral under test and the reference ore were crushed and pulverized in the laboratory milling machine for an hour (60 minutes);

(ii). the samples of test and reference mineral were taken and sized by sieving into a number of size fraction using the automatic sieve shaker for 60 minutes;

(iii).each size fraction of the test and the reference mineral were weighed and the value noted as “feed”;

(iv). the “feed” test and reference mineral were each gathered together and introduced into the laboratory mill machine and ground for 60 minutes;

(v). the test and the reference mineral from the laboratory ball mill machine were sized and each sieve fraction was weighed and the value noted as the product or discharge and

(vi). the ground samples were sieved into the following sieve size fractions; +1400 μm,-1400 μm + 1000 μm, -1000 μm +710 μm, -710 μm +500 μm, -500 μm + 355 μm, -355 + 250 μm, -250 μm + 180 μm, -180 μm +125 μm, -125 μm +90 μm, -90 μm +63 μm, -63 μm using automatic Denver sieve shaker for 60 minutes.

CHAPTER FOUR

4.0. RESULTS

4.1. Hardness Values

Table 1 of Appendix I gives the hardness values of as-received samples A and B and samples C and D developed plates while Figure 4.1 shows the bar chart of the hardness values (HBN) of the two samples of as-received and two samples of developed plates.

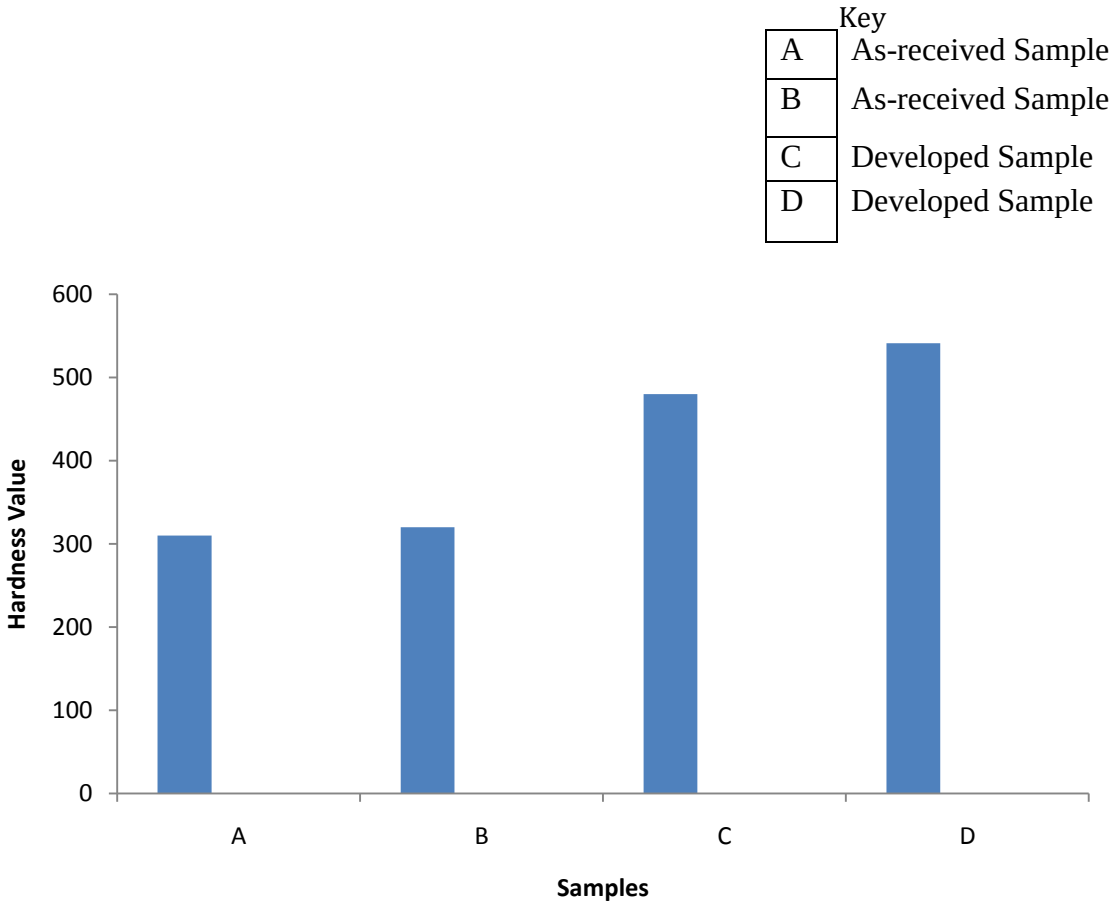


Figure 4.1: Bar chart of the hardness values of the as-received and developed grinding plate

4.2. Impact Values

Table 2 of Appendix I gives the impact energy values absorbed by the as-received and the developed samples while. Figure 4.2 shows the bar chart of their impact energy.

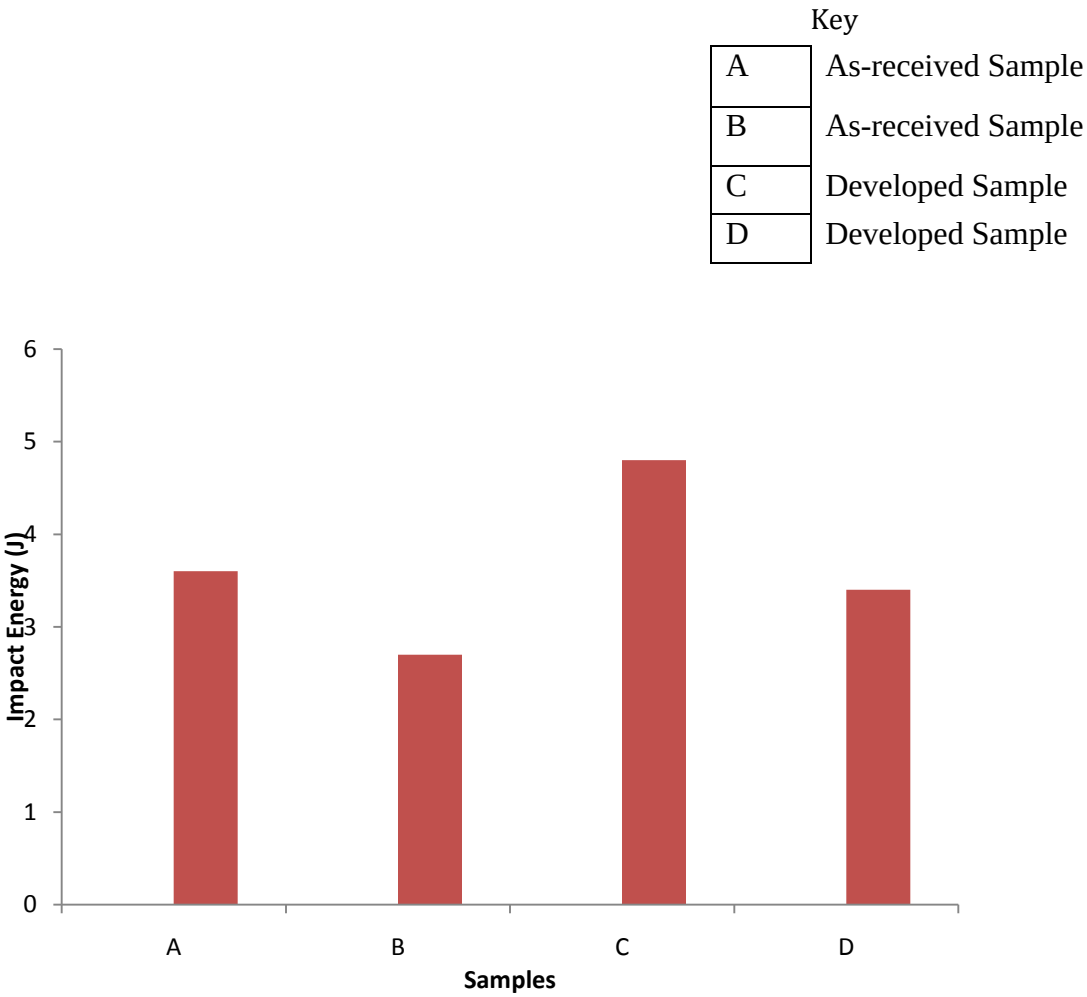


Figure 4.2: Bar chart of the impact energy absorbed by the as-received and developed grinding plate samples.

4.3. Wear Rate Results

The wear rate results of the as-received samples A and B, and the developed samples C and D are presented in Tables 3-6 of Appendix I while Figure 4.3 shows the results of wear rate against cumulative duration used in grinding before worn out of each faces.

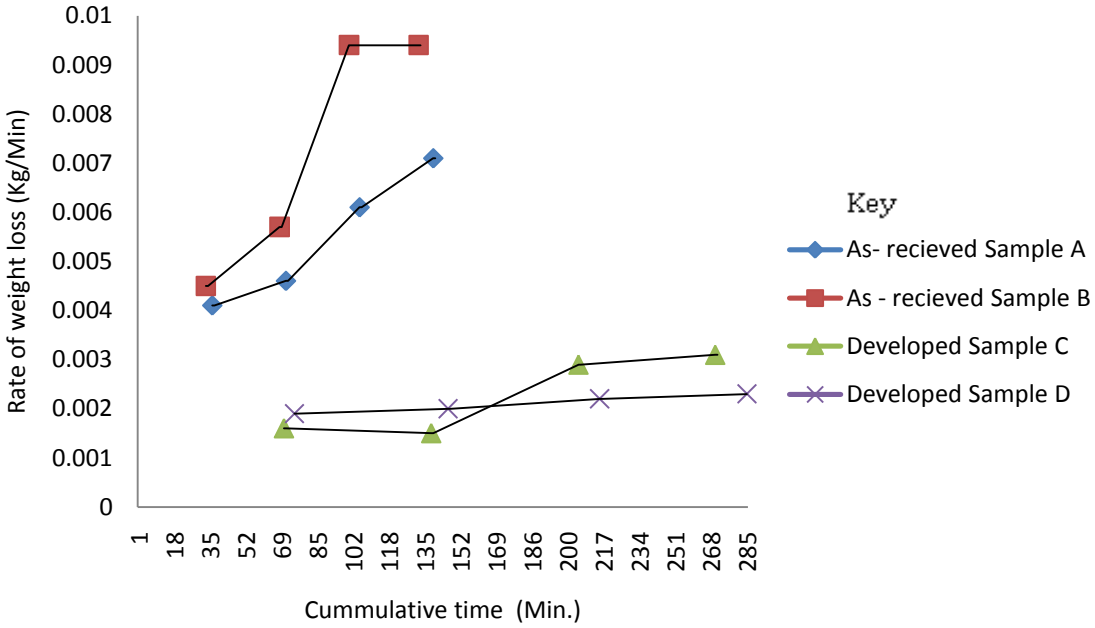


Figure 4.3: Rate of weight loss (Kg/min) against cumulative time.

4.4. Average Wear Rate of the as-received and developed Samples and their Corresponding Hardness Values

The average wear rate of the as-received samples A and B and the developed samples C and D with their corresponding hardness values are presented in Table 7 of Appendix I. Figure 4.4 shows the graph of average wear rate of each sample and the hardness values.

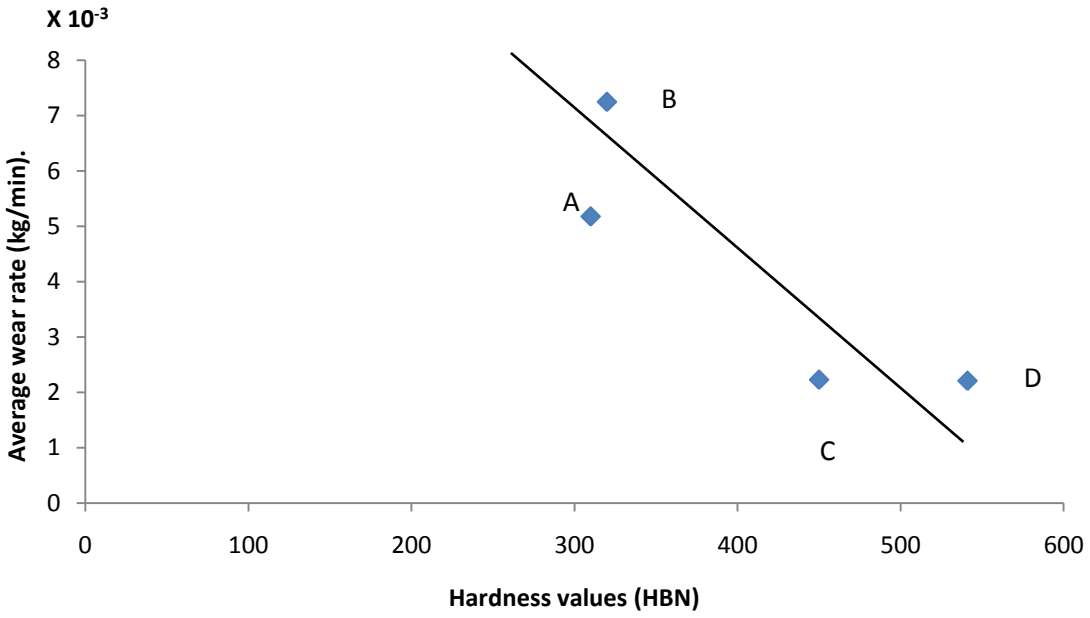


Figure 4.4: Graph of average wear rate of each sample and the corresponding hardness value

4.5. Microstructural results

The microstructure of the as-received samples A and B and developed samples C and D are shown in plates 4.1, 4.2 and plates 4.3 and 4.4 respectively.

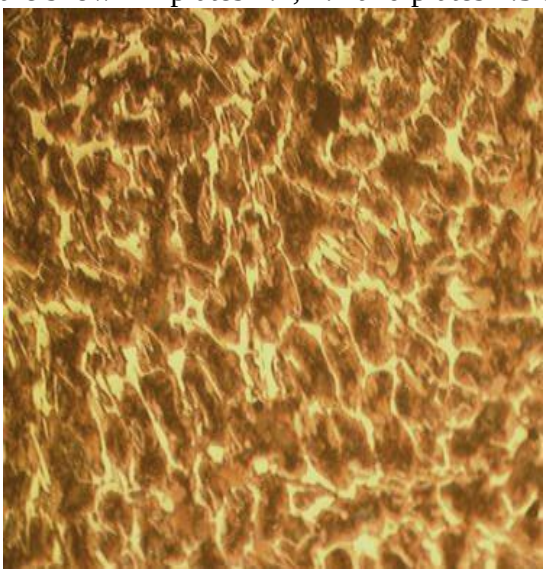


Plate 4.1
Microstructure of the as-received sample A. The dark portions represent pearlite, while the white portions is cementite phase (100X)

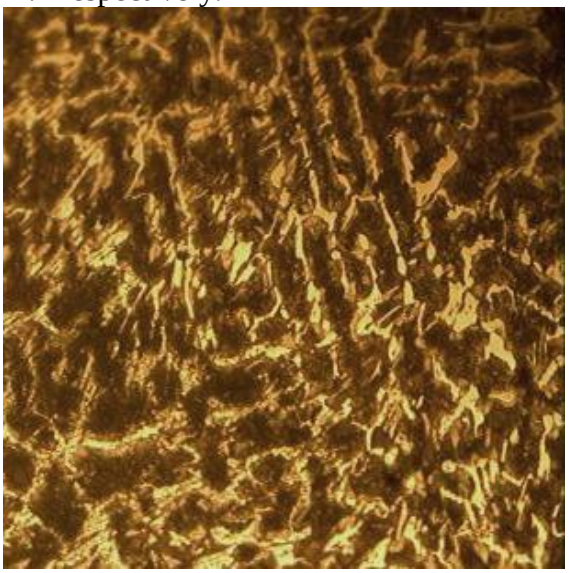


Plate 4.2
Microstructure of the as-received sample B.

dark portions represent pearlite, while white portions is cementite phase (100X)

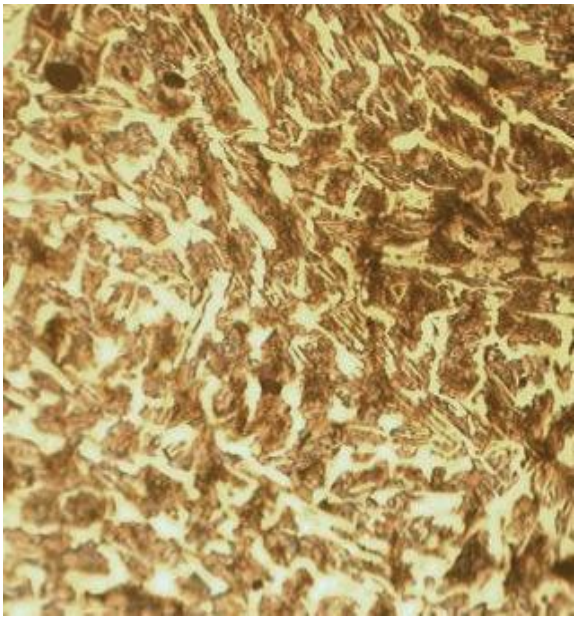


Plate 4.3.
Microstructure of developed sample C. The dark portions represent pearlite, the white Portion is cementite phase (100X)

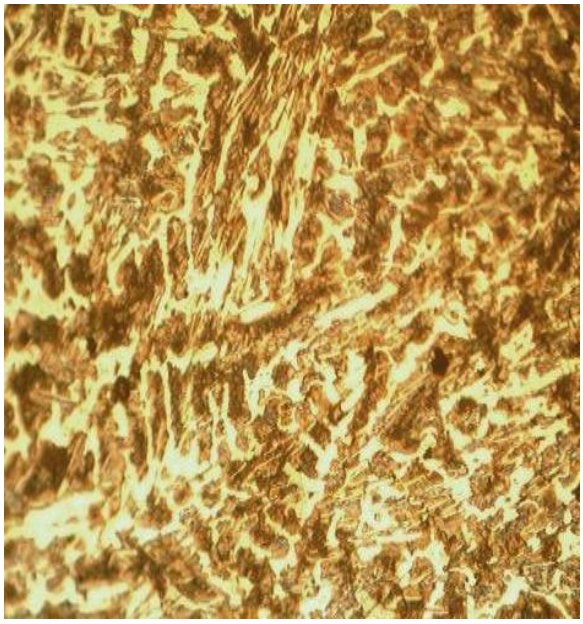


Plate 4.4.
Microstructure of developed sample D. The dark portions represent pearlite, the white portion is cementite phase (100X)

4.6. Highlighted in Tables 4.1 – 4.4 are the chemical analysis results of the gold-bearing mineral samples 1 and 2, the hardness and impact values of the mineral samples and the as-received grinding plates sample A and B, respectively.

Table 4.1: Chemical composition of the Gold-bearing Mineral Sample 1

Channel	Si	K	Ca	Ti	Cr	Mn	Fe	Ni	Zn	As	Y	Ru	Re	Au	Pb	Cu
Compound	SiO_2	K_2O	CaO	TiO_2	Cr_2O_3	MnO	Fe_2O_3	NiO	ZnO	As_2O_3	Y_2O_3	RuO_2	Re_2O_7	Au	PbO	CuO
Concentration Unit %	97.0	0.20	0.041	0.060	0.050	0.119	1.60	0.010	0.004	0.305	0.017	0.339	0.026	0.096	0.14	0.055

Table 4.2: Chemical composition of the Gold-bearing Mineral Sample 2

Channel	Si	K	Ca	Ti	V	Cr	Mn	Fe	Ni	Cu	As	Au	Ru	Eu	Yb	Os	Pb	Y
Compound	SiO_2	K_2O	CaO	TiO_2	V_2O_5	Cr_2O_3	MnO	Fe_2O_3	NiO	CuO	As_2O	Au	RuO	Eu_2O	Yb_2O_3	OsO_4	PbO	Y_2O_3
Concentration Unit %	91.8	0.635	0.047	0.14	0.005	0.090	0.574	6.11	0.005	0.065	0.036	0.012	0.35	0.08	0.01	0.010	0.037	0.017

Table 4.3: Hardness and impact values of the gold bearing mineral sample 1 and 2

	Mineral Sample 1	Mineral Sample 2
Impact values (Joules)	0.7	0.5
Hardness values (HBN)	361	342

Table 4.4: Chemical compositions of the as-received grinding plate sample A and B

Elements	C	Mn	S	P	Si	Cr	Mo	Ni	Cu	Al	V	Nb	B	Ti	Fe
Sample A	3.28	0.40	0.188	0.301	1.980	0.001	0.011	0.091	0.35	0.010	0.011	0.007	0.009	0.008	Balance
Sample B	3.19	0.30	0.110	0.058	2.181	0.003	0.021	0.104	0.30	0.013	0.010	0.008	0.0093	0.010	Balance

4.7. The work index of the mineral

The work index of the gold bearing minerals was determined; details are presented in Tables 1 to 6 of Appendix II. Table 1 and 2 shows both the sieve analysis results of the feed to the Ball Mill and the product of the Ball Mill for test mineral sample 1. Also, Table 3 and 4 shows the sieve analysis results of feed to the Ball Mill and Product of the Ball Mill for the test mineral sample 2 while Table 5 and 6 shows the sieve analysis results of feed to the Ball Mill and product of the Ball Mill for the reference mineral respectively.

CHAPTER FIVE

5.0. DISCUSSION OF THE EXPERIMENTAL RESULTS

5.1.0. Mechanical Properties of the Investigated Samples

5.1.1. Hardness properties of the as-received and developed samples

The hardness value increases with the addition of alloying elements as given in Table 1 of the Appendix I and graphically represented in Figure 4.1. The hardness increases from 480 HBN to 541 HBN; this may be as a result of the compositional differences in the developed samples. Sample D revealed the highest hardness value of 541 HBN followed by sample C, 480 HBN. Samples A and B show close hardness value of 320 HBN and 310 HBN respectively. The observed hardness values in the developed samples C and D are within the acceptable range of hardness expected to be found in white iron base grinding plate while the values obtained in the as-received samples A and B are within the established range of grey cast iron base grinding plate (www.basics of design engineering). It is also an indication that the as-received samples A and B are unalloyed and as such have limited areas of application. This is an attestation to the fact that high hardness value promotes high wear resistance while low hardness increases the wear rate (Halling, 1987). Hardness is related to wear in that if it is very difficult to break one bond, then the chances of breaking many bonds (wear) will be low (Myer, 2002). Samples C and D have been adjudged satisfactory for use in a situation that requires abrasive wear resistance.

Based on the hardness values of the gold-bearing mineral highlighted in Table 4.3, sample 1 has higher hardness value of 361 HBN, thereby possessing higher resistance to grinding as compared to sample 2 with lower hardness value of 341 HBN. This observation is in

support of the fact that hardness could further be defined as the resistance of a surface to abrasion or scratching (Higgins, 1993; Meyer, 1999, Myer, 2002). An early attempt to measure surface hardness was based on this concept, of using a harder object to scratch off another object, and then make deduction for their hardness value. While such methods undoubtedly reflect true concept of hardness, they have been abandoned in favour of methods which are capable of greater accuracy but in which the resistance of the surface layers to plastic deformation under static pressure is measured (Higgins.1993; Halling, 1987; Meyer, 1999). In most of these methods, the static force used is divided by the numerical value of the surface area of the resulting impression to obtain the hardness index value.

5.1.2. The impact strength of the as-received and developed samples

The principal measurement from the impact test is the energy absorbed in fracturing the specimen. The energy absorbed in fracture usually expressed in joules is read directly from a calibrated dial on the impact tester. The impact values of the as-received samples A and B and the developed samples C and D are given in Table 2, of Appendix I. Figure 4.2 shows the bar chart of the impact values of all the samples. Sample C has the highest impact value of 4.8 joules followed by sample A with a value of 3.8 joules while sample D and B have energy impact values of 3.4 and 2.7 joules respectively. The variation in the obtained impact values could be attributed to the compositional differences, in the investigated samples. Sample D is more brittle, but it has good hardness value and wear resistant ability. Both samples A and B show high disparity in their values, indicating the inability of the producer to develop exact quality during production process. Although,

sample D has lower impact value when compared with sample C, it has the potential of being used for the fabrication of Bagega gold-bearing mineral grinding plates.

From the impact values of the mineral samples 1 and 2, given in Table 4.3, higher energy is being required to break sample 1 with higher energy value of 0.7 joules than sample 2 with energy value of 0.5 joules.

5.2. Wear Rate Values of the Investigated Samples

5.2.1. As- received sample A

It can be deduced from Table 3 of Appendix I and Figure 4.3 that the wear rates of the grinding face of sample A occurred within a short time of thirty- six minutes in grinding operations. This led to low output and frequent down-time in service. It could be attributed to poor mechanical properties such as low hardness and low abrasive wear resistance of the sample. In essence the component does not possess the desirable properties to be of commercial equipment manufacturing due to its low resistance to wear. The maximum weight loss of 0.25 kg in thirty five minutes is still an indication of high rate of wear that resulted in rapid rate of thickness reduction coupled with a delay in service. The behaviour is in conformity with the third law of abrasive wear; which states that “The volume of wear material is inversely proportional to the hardness or yield strength of the material” (Halling, 1987).

5.2.2. As- received sample B

Based on the appended data in Table 4 of Appendix I and Figure 4.3, sample B has a high wear rate value of 0.30 kg, indicating poor mechanical properties in terms of hardness and resistant to abrasive wear while in service. It was observed that within thirty three

minutes, one of the grinding faces had to be replaced due to wear. This resulted in low production output due to incessant occurrence of operational down- time. In addition to a maximum weight loss of 0.30 kg in thirty three minutes; the overall duration of the component in service was one hundred and thirty one minutes. In comparism with sample C and D, Such component cannot serve optimally for a commercial production due to high wear rate.

5.2.3. Developed sample C

While there was an increase in grinding operation up to seventy minutes using the developed sample C grinding plate, a reduction in grinding plate weight loss became noticeable. The maximum weight loss was 0.2 kg within sixty seven minutes in use. The sample had an accumulated duration of two hundred and seventy minutes, with insignificant loss in weight. This improvement reduces operation down-time and increases output by resisting rapid abrasive wear by the charged mineral. It can be deduced from Table 5 of Appendix I and Figure 4.3 that the developed sample C, possessed high mechanical and wear resistant properties to overcome operation down-time, coupled with increasing output.

5.2.4. Developed sample D

Based on data of Table 6 of Appendix I and Figure 4.3, a lower wear rate over a long period of operation of more than seventy minutes before a face worn-out was developed using sample D. It indicates long service duration with maximum weight loss of not more than 0.16 kg per face. It also indicates the resistance of the sample to abrasive wear by the

charged minerals which leads to longer service duration before a face worn-out was observed. This can be attributed to high mechanical properties which lead to operational high output and reduction in down-time during production process.

5.3. Correlation between the Average Wear Rate and Hardness Values

As can be deduced from Figure 4.4 and Table 7 of Appendix I, the higher the hardness value, the lower the wear rate. Conversely, the lower the hardness value, the higher the wear rate. The average wear rate values of sample A and B were very close with little variation in value, just as their hardness values. Sample C and D have lower wear rate with considerable increase in hardness compared with sample A and B. Higher hardness value of 541 HBN obtained from sample D revealed a clear indication of the presence of the alloying elements, (such as ferro-chrome, ferro-molybdenum and nickel) that enhance the hardness properties to various level. That is, increase in the percentage of the alloying elements from 2.0 %wt to 3.5 %wt in sample C and D respectively contributes to such effect, in addition, sample D has 0.8 %wt of molybdenum (Laird, 1991; Robert, 2011; Gilder, 1960). The presence of the molybdenum and the percentage increase in ferrochrome could be the cause of higher hardness value and wear resistant rate in Sample D. The correlation curve between the wear rate and hardness values (Figure 4.4) is in agreement with the third law of abrasive wear, which states that, "the volume of wear material is inversely proportional to the hardness or the yield strength of the material" (Halling, 1987). In addition the results indicate that 'hardness' is a vital parameter when considering wear resistance material. It equally indicates that the rate of wear is inversely proportional to the hardness of the plates.

5.4. Microstructural Analysis of the Investigated Samples

5.4.1. As- received sample A

The microstructure of the as-received sample plate A, shown in plate 4.1 reveals the presence of pearlite structure (dark spots) and cementite structure, which is white. The pearlite structure with tiny strands of cementite is mixed, the latter structure is lesser than the former structure in appearance, and this could be the reason for the poor mechanical properties of the samples. It shows that the structure is unalloyed cast iron that has weak matrix because of the dominant phase of pearlite present which is in conformity with the characteristic structure of grey cast iron reported previously (Laird, 1991; Gilder, 1960; Higgins, 1993; Robert, 2011; Sighn 2012).

The possibility of this sample to withstand abrasive wear is low because of the weak dominant structure and the presence of few cementite phases that can promote hardness characteristics of the component. As earlier claimed by previous investigators, wear can be minimized effectively by the presence of hard phases like carbides, boride or nitride in the tool or work piece (Jackson, 2007, Liard 1991; Andrew, 2005).

5.4.2. As- received sample B

The microstructure shown in plate 4.2 consists of coarse dark spot which is pearlite structure with tiny white strands of cementite structure. It can be inferred from the structure that the sample is an unalloyed grey cast iron with low tendency to form strong carbides that can promote high hardness and wear resistance due to the presence of dominant pearlitic structure (dark spots) in the matrix, accompanied by few cementite structure. In essence the presence of pearlitic structure suggests susceptibility of low hardness and rapid wear rate due to weak nature of the matrix. Based on previous research

findings, any grinding plate that will be able to withstand rapid material loss due to wear should possess hard phases like carbides, borides or nitride in the work piece so that it can impart the required mechanical properties (Jackson, 2007, Liard 1991; Andrew, 2005).

5.4.3. Developed sample C

The microstructure of the developed sample C shown in plate 4.3 reveals a matrix of pearlite structure (dark spots) accompanied by a white cementite structure, which accounts for the highest level overall total structure obtained in the sample. The prevalence of cementite structures over the structures of pearlites promotes hard matrix structure with high wear resistant value. The obtained structure indicates the presence of alloying elements such as chromium and nickel which forms carbides that can promote high hardness and wear resistance developed in the sample. The carbide formed by these alloys also has the tendency to withstand high temperature as well as possessing good mechanical properties – characteristic of white cast iron that is being used for high wear resistant applications. The revealed characteristics of the developed sample C is in agreement with the previous work (Laird, 1991; Jackson, 2007; Robert, 2011). The established characteristics of the developed sample C affirmed the fact that the development of a high wear resistant material is being enhanced by hard phases like carbides, borides, nitrides that are capable of withstanding high abrasive wear rate (Laird, 1991; Jackson, 2007; Robert, 2011).

5.4.4. Developed sample D

The effect of ferrochrome and other alloying elements as carbide formers is being established in the microstructure of plate 4.4 showing the prevalence of a white cementite structure accompanied by few pearlite structures. A considerable increase in hardness and

wear resistant properties were obtained due to higher level of carbide present in the structure. This is in conformity with the developed carbide found in chromium alloyed cast iron as reported in previous research findings

(FOSECO, 1994; Kwofie, 2012). This is an established conventional method of producing white cast iron in which chromium is being identified as a notable carbide former ensuring that the carbon remains combined as iron carbide as the casting products cooled to room temperature. The on-going findings are in agreement with previous finding that has affirmed that for a material to be used for high wear resistant application most be able to develop hard phase, such as carbides, borides, nitrides capable of withstanding high abrasive wear rate.

5.5. The Chemical Analysis of Gold-bearing Mineral

The samples of the gold-bearing mineral were characterized using ED-XRF machine to study their chemical constituents. It was observed that sample 1 of the mineral shows the appearance of gold at 0.096 %, while the dominant compound was silicon oxide (SiO_2), at 97.0 %. They were other compounds present as shown in Table 4.1- 4.2 Sample 2 also indicates 0.012% appearance of gold which is very minute while the dominant compound was silicon oxide (SiO_2) at 91.8 %. It shows clearly that the compositions of the mineral from various sites are not the same; this confirms the fact that it is very possible for the samples to differ in hardness and other properties, thereby posing different challenges in the gold-ore beneficiation process.

5.6. The Chemical Analysis of the As- received Grinding Plates Samples

Based on highlighted chemical composition of the as- received grinding plates sample A and B in Table 4.4, it can be easily deduced that the plates were grey cast iron plates and

unalloyed, that lack some elements that are capable of improving its mechanical properties for the intended function. The major prevailing elements are silicon, manganese, and sulphur with percentage composition of 2.18, 4.40 and 0.188 respectively. These are the dominant elements found in grey cast iron, with very low quantity of carbide forming elements such as chromium, nickel, copper, vanadium and molybdenum. However, the percentage compositions of these elements are below the recommended standard that should be required for carbide formation in the investigated samples according to the ASTM 532A standard, which described the ranges of compositions suitable for such application.

5.7. The Work index of the Gold-bearing Minerals

The most widely used parameter for measuring ore grindability is the Bond Work Index W_i. Work index is the energy required in (Kwh/ton) to reduce a given material from theoretical infinite size to 80 % passing size of 100 microns (Gupta, 2003). It could further be explained as the resistance of ore to grinding or crushing. This is basically an indication of the ore hardness value properties (Starkey and David, 2008; Gupta, 2003; Andre and Steve, 2005). Bond Work index is useful in designing of grinding system in mineral processing. It is also the measure of ore grindability, which is the ease at which the mineral can be grinded (Gupta, 2003). The higher the sample hardness value, the higher the energy required for its grinding (Oladunni, 2012; Gupta, 2003). The work index of the gold-bearing minerals was determined through an alternative Bond method known as Berry and Bruce method (Oladunni, 2012; Gupta, 2003). Despite the fact that the two gold-bearing ore deposits were from the same location, the variation in work index values of 14.30 Kwh/ton and 12.29 Kwh/ton for samples 1 and 2 respectively could

be attributed to the fact that the investigated gold-bearing mineral sample 1 contains higher percentage of both silica and gold content and other hard compounds that would have been responsible for the obtained higher work index value than sample 2. Table 8 – 13 of Appendix II contains the detail of the analysis.

5.8. Cost to Manufacture New Grinding Plate

The final decision on a manufacturing process is usually made on the basis of the cost to make a part; called the unit cost. According to Dieter and Schmidt (2013), the cost to manufacture a part is made up of the cost of the material, the wages of the persons who made the part, the cost of tooling, a payment to the over time receivers, the capital cost of equipment and an over head cost that lumps together making general factory costs that cannot be readily associated with each part made. However, the total unit cost of a part will depend on:

(a) material cost, the number of parts, but strongly dependent on its mass,

(b) tooling cost that varies inversely with the number of parts and

(c) capital equipment cost and over head cost which vary inversely with the rate of production. These dependencies lead to the concept of economic production size factor that is the number of parts at which the unit cost of one process becomes lower than that of its competitors. The grinding needs of Bagega gold-bearing mineral processing operation will be adequately met at an estimated cost of eleven thousand naira (11,000.00) being a rough estimate of the overall cost of the highlighted parameters that go into that production of the developed grinding plates. In essence some level of achievement has been attained by the enhancement of the service life of the grinding plate used by the local gold-bearing mineral processors. This has led to an appreciable reduction in service down-

time in grinding operation. Highlighted procedures for quick replacement of the worn-out grinding plates will lead to cost saving in the production process and the overall cost per unit item

CHAPTER SIX

6.0. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

6.1. Summary

The failure analysis of the as-received grinding plates used in processing gold-bearing mineral found in Bagega Village, Anka Local government area of Zamfara State, has shown that the rapid abrasive wear rate of the grinding plates which leads to thickness reduction and fracture occurred due to low quality of the work piece. It has been stated that, a material that should be used for mineral grinding and crushing should be able to provide high mechanical strength that can trench the solid matter charged in the grinding media by overcoming the strength of interior bonding forces of the solid matter (Broeckmann and Guardula, 2005). Such material must possess hard phases distributed in soft tissue matrix, excellent wear resistance, hardness, high damping capabilities, so that the desirable qualities needed for grinding will be provided (Jackson, 2007).

The chemical composition of the as-received grinding plate samples has revealed an evidence of an unalloyed grey cast iron. The main elements of unalloyed cast iron are carbon, silicon, sulphur, manganese, and phosphorus, which are dominant in samples A and B, with low level of elements that can promote high hardness properties. They have average bulk hardness values of 320 HBN and 310 HBN respectively while sample C and D have average bulk hardness values of 480 HBN and 541 HBN respectively. From the microstructural analysis of samples A and B, appearances of pearlite (dark spot) and cementite (white) structure were revealed, with dark portion dominating the phases in both samples. It is an indication that the samples are prone to low hardness and rapid wear rate since the matrix is weak. The obtainable microstructure in sample C and D indicate

high percentage of the presence of cementite structure in their matrix which gives high hardness and wear resistance properties. The characteristic properties displayed by sample C and D, is in conformity of what the material for mineral grinding and crushing should possess to affect service durability (Laird, 1991; Gilder, 1960; Higgins, 1993; Robert, 2011).

The mode of fracture observed from the as-received sample A and B are brittle fracture, indicating that their failure mode is rapid without tenacity or yielding. It clearly shows that the materials were not toughened, any abrupt impact is liable to induce crack. Sample C and D tested in the same service conditions of sample A and B did not display any form of fracture, even at the cumulative duration of two hundred and eighty five minutes in service. This is an indication of improvement in the mechanical properties, probably from the compositional adjustment made.

The engine mode of vibration in service were observed to be stable, the basement were able to provide damping strength to absorb the vibration forces. The crack observed from the as-received part within the nut fixing holes came merely by the inability of the work piece to provide the necessary mechanical properties desirable for such work.

The work index of the gold-bearing minerals was determined to be 14.30 Kwh/ton and 12.29 Kwh/ton in sample 1 and 2 respectively. However sample 1 with work index of 14.30 Kwh/ ton is not far from the established standard gold work index of 14.83 Kwh/ton (Perry et al, 2006). Therefore possession of good grinding tools for our local industries is a head way to achieve optimum productivity with less down- time and an improvement in our local production in the areas of mineral beneficiation.

6.2. Conclusions

The following conclusions could be drawn from the results obtained from the experimental tests:

1. The as-received plate samples lacked adequate mechanical properties to promote grinding of the minerals for a longer period without experiencing rapid wear and fracture, which prompt the failure of plates within a short time.
2. Materials that can promote high mechanical properties such as hardness and wear resistance were not incorporated in the alloy compositions of the as-received grinding plates.
3. Appropriate material selection, design and development are the best method to minimized failure.
4. The work index of the gold-bearing mineral sample 1 is 14.30Kwh/ton and that of sample 2 is 12.29 Kwh/ton.
5. The developed white iron samples have the potential to serve longer in service.

6.3. Recommendations

1. It is being recommended that the work index of the gold-bearing mineral should be determined through other methods to ensure comparative values.
2. Wet grinding of the gold-bearing mineral is also recommended as an alternative means of grinding to enable the plates to last longer in service.
3. Further research work should continue in the areas of enhancing the impact strength (toughness) of the developed samples so that their areas of application

will not be limited to attrition mills alone, rather to other mineral processing mills of higher capacity.

6.4. Contribution to Knowledge

In this research work, causes of rapid failure of the grinding components of Bagega gold milling machine has been established, an alternative component that can serve optimally in Bagega gold-bearing mineral grinding using attrition mills has been developed, as well as the work index of the gold-bearing minerals. The quantity of supply of the Bagega gold-bearing mineral samples to the international gold market to earn foreign exchange for the nation will be enhanced.

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Appendix I: Hardness values of the as-received and developed samples, impact values and wear rate values.

Table 1: Hardness values of both the as – received and the developed samples

Samples	As-received samples		Developed samples	
	A	**B**	**C**	**D**
Hardness values (HBN)	**310**	**320**	**480**	**541**

Table 2: Corresponding impact energy absorbed by the as-received and the developed samples

Samples	As-received samples		Developed samples	
	A	**B**	**C**	**D**
Impact values (J)	**3.8**	**2.7**	**4.8**	**3.4**

Table 3: Wear rate of the as – received sample A

Faces	**Initial Weight, W_b (Kg)**	**Final weight, W_f (Kg)**	**Weight loss W_l (Kg)**	**Time (T) (Min.)**	**Cumulative Time (Min.)**	$Wear\ rate$ **Wr x 10^{-3} (Kg/min)**
Face 1	3.30	3.14	0.15	36	36	4.1
Face 2	3.14	2.98	0.16	35	71	4.6
Regrooved Face 1	2.50	2.30	0.20	33	104	6.1
Regrooved Face 2	2.30	2.05	0.25	35	139	7.1

Table 4: Wear rate of the as – received sample B

Faces	Initial Weight, W_b (kg)	Final Weight, W_f (Kg)	Weight loss, W_l (Kg)	Time (T) (Min.)	Cumulative Time (Min)	$Wear\ rate$, Wr x 10^{-3} (Kg/min)
Face 1	3.30	3.15	0.15	33	33	4.5
Face 2	3.15	2.95	0.20	35	68	5.7
Regrooved Face 1	2.50	2.20	0.30	32	100	9.4
Regrooved Face 2	2.20	1.90	0.30	32	132	9.4

5: Wear rate of the developed sample C

Faces	Initial Weight, W_b (kg)	Final Weight, W_f (Kg)	Weight loss, W_l (Kg)	Time(T) (Min.)	Cumulative Time (Min)	$Wear\ rate$ Wr x 10^{-3} (Kg/min)
Face 1	3.50	3.39	0.11	70	70	1.6
Face 2	3.39	3.29	0.10	68	138	1.5
Regrooved Face 1	3.00	2.80	0.20	67	205	2.9
Regrooved Face 2	2.80	2.60	0.20	65	270	3.1

Table 6: Wear rate of the developed sample D

Faces	Initial Weight, W_b (Kg)	Final Weight, W_f (Kg)	Weight loss, W_l (Kg)	Time (T) (Min.)	Cumulative Time (Min)	$Wear\ rate$ Wr x 10^{-3} (Kg/min)
Face 1	3.50	3.34	0.16	75	75	2.1
Face 2	3.34	3.20	0.14	71	146	2.0
Regrooved Face 1	2.90	2.75	0.15	69	215	2.2
Regrooved Face 2	2.75	2.59	0.16	70	285	2.3

Table 7: Average wear rate of the as-received and the developed samples and their corresponding hardness values

	As- received Samples		Developed Samples	
Faces	A	B	C	D
Face 1	4.1	4.5	1.4	2.1
Face 2	4.6	5.7	1.5	2.0
Regrooved Face 1	6.1	9.4	2.9	2.2
Regrooved Face 2	7.1	9.4	3.1	2.3
Average Wear rate (10^{-3})	5.48	7.25	2.23	2.15
Hardness Values (HBN)	310	320	450	541

Appendix II: Evaluation of the work index of the Gold-bearing Minerals.

Results of Sample 1, Sample 2 and Reference Sample 3 are presented in Tables 1 – 6

Table 1: Sieve analysis result of the feed to Ball Mill of Test Mineral Sample 1

Sieve Size Range (µm)	Weight retained (g)	% Weight retained	Cumulative % weight retained	Cumulative % weight Passing
+1400	12.52	12.52	12.52	87.48
-1400 + 1000	15.83	15.83	28.34	71.66
-1000 + 700	13.54	13.54	41.88	58.12
-700 +500	11.64	11.64	53.52	46.48
-500 +355	9.87	9.87	63.39	36.61
-355 +250	8.54	8.54	71.93	28.07
-250 +180	8.62	8.62	80.55	19.45
-180 +125	8.41	8.41	88.86	11.04
-125 +90	6.55	6.55	95.51	4.49
-90 +63	2.52	2.52	98.03	1.97
-63	1.96	1.96	100.0	-

Calculation 1:

If 1000 µm = 71.66%
X µm = 80%
$X = \frac{80 \times 1000}{71.66} = 1117.32$ µm

Table 2: Sieve analysis results of the Product of Ball Mill of Test Mineral Sample 1

Sieve Size Range (µm)	Weight retained (g)	%Weight retained	Cumulative % weight retained	Cumulative % weight Passing
+1400	-	-	-	100
-1400 + 1000	-	-	-	100
-1000 + 700	-	-	-	100
-700 +500	0.22	0.22	0.22	99.78
-500 +355	0.53	0.53	0.75	99.25
-355 +250	13.60	13.60	14.35	85.65
-250 +180	49.88	49.88	64.23	35.77
-180 +125	19.33	19.33	83.56	16.44
-125 +90	10.80	10.80	94.36	5.64
-90 +63	3.50	3.50	97.86	2.14
-63	2.14	2.14	100.0	-

Calculation 2:

If 1000 µm = 100%

X µm = 80%

$X = \frac{80 \times 1000}{100}$

X =800.00 µm

Table 3: Sieve analysis results of the feed to Ball Mill of Test Mineral Sample 2

Sieve Size Range (µm)	Weight retained (g)	% Weight retained	Cumulative % weight retained	Cumulative % weight Passing
+1400	16.14	16.14	16.14	83.86
-1400 + 1000	16.82	16.82	32.96	67.04
-1000 + 700	13.12	13.12	46.08	53.92
-700 +500	10.24	10.24	56.32	43.68
-500 +355	7.20	7.20	63.52	36.48
-355 +250	5.62	5.62	69.14	30.86
-250 +180	5.75	5.75	74.89	21.11
-180 +125	5.19	5.19	80.08	19.92
-125 +90	9.02	9.02	89.10	10.90
-90 +63	6.20	6.20	95.30	4.70
-63	4.70	4.70	100.0	-

Calculation 3

If 1000 µm = 67.04%

X µm = 80%

$X = \frac{80 \times 1000}{67.04} = 1193.32$ µm

Table 4: Sieve analysis results of the Product of Ball Mill of Test Mineral sample 2

Sieve Size Range (µm)	Weight retained (g)	% Weight retained	Cumulative % weight retained	Cumulative % weight Passing
+1400	-	-	-	100
-1400 + 1000	-	-	-	100
-1000 + 700	0.31	0.31	0.31	99.69
-700 +500	0.60	0.60	0.91	99,09
-500 +355	3.71	3.71	4.62	95.32
-355 +250	19.70	19.70	24.32	75.62
-250 +180	44.77	44.77	69.09	30.85
-180 +125	18.61	18.61	87.70	12.24
-125 +90	8.40	8.40	96.10	3.84
-90 +63	2.60	2.60	98.70	1.24
-63	1.30	1.30	100.0	-

Calculation 4:

If 1000 µm = 100%
X µm = 80%
$X = \frac{80 \times 1000}{100} = 800$ µm

Table 5: Sieve analysis results of the feed to Ball Mill of Reference Mineral sample 3

Sieve Size Range (µm)	Weight retained (g)	% Weight retained	Cumulative % weight retain	Cumulative % weight Passing
+1400	13.00	13.00	13.00	87.00
-1400 + 1000	15.11	15.11	28.11	71.89
-1000 + 700	13.13	13.13	41.24	58.76
-700 +500	11.42	11.42	52.66	47.34
-500 +355	9.67	9.67	62.33	37.67
-355 +250	8.10	8.10	70.43	29.57
-250 +180	7.82	7.82	78.25	21.75
-180 +125	6.24	6.24	84.49	15.51
-125 +90	7.49	7.49	91.98	8.02
-90 +63	4.12	4.12	96.10	3.90
-63	3.90	3.90	100.0	-

Calculation 5:

If 1000 µm = 71.89%
X µm = 80%
$X = \frac{1000 \times 80}{71.89}$
X = 1112.81 µm

Table 6: Sieve analysis results of the Product of Reference Mineral sample 3

Sieve Size Range (µm)	Weight retained (g)	% Weight retained	Cumulative % weight retained	Cumulative % weight Passing
+1400	-	-	-	100.00
-1400 + 1000	0.51	0.51	0.51	99.49
-1000 + 700	1.12	1.12	1.72	98.28
-700 +500	2.01	2.01	3.73	96.27
-500 +355	3.12	3.12	6.85	93.15
-355 +250	22.02	22.02	28.87	71.13
-250 +180	56.03	56.03	84.90	15.10
-180 +125	8.32	8.32	93.22	6.78
-125 +90	3.82	3.82	97.04	2.96
-90 +63	1.63	1.63	98.67	1.33
-63	1.42	1.42	100.0	-

Calculation 6:

If 1000 µm = 99.49
X µm = 80%
$X = \frac{80 \times 1000}{99.49}$
= 804.10 µm

Modified Bond's equation states that
$W = Wt = Wir = (10/\sqrt{Pr} - 10/\sqrt{Fr}) = Wit = (W/\sqrt{Pt} - W/\sqrt{Ft})$ (Bond,1952)

Therefore

$$Wit = Wir \frac{(10/\sqrt{Pr} - 10/\sqrt{Fr})}{(W/\sqrt{Pt} - W/\sqrt{Ft})}$$

Where, Wir = work index of the reference ore

Wit =Work index of the test ore

Pr = The diameter of the reference ore product, 80% of which passes through 100µm aperture

Pt = The diameter of the test ore product, 80% of which passes through 100µm aperture

Fr = The diameter of the reference ore feed, 80% of which passes through 100µm aperture

Ft = The diameter of the test ore feed, 80% of which passes through 100µm aperture

Wr =Work input in Kilowatt hour/short ton for reference ore and

Wt = Work input in Kilowatt hour/short for test ore

1. Considering Furaka Granite as reference mineral for sample 1
   Ft = 1117.32 µm
   Fr =1112.81 µm
   Pt = 800.00 µm
   Pr= 804.10 µm
   $$Wit = \frac{Wir\ (10/\sqrt{Pr} - 10/\sqrt{Fr})}{(10/\sqrt{Pt} - 10/\sqrt{Ft})}$$
   Where,
   Wir =15.13 for granite

   $$Wit = \frac{15.13(10/\sqrt{804.10} - 10/\sqrt{1112.81})}{10/\sqrt{800.00} - 10/\sqrt{1117.32}} = 14.30 \text{Kwhs/ton}$$

2. Considering Furaka Granite as reference mineral for sample 2
   Ft_b =1193.32 µm
   Fr = 1112.81 µm
   Pt_b = 800 µm
   Pr = 804.10µm

   $$Wit = \frac{Wir\ (10/\sqrt{Pr} - 10/\sqrt{Fr})}{(10/\sqrt{Pt} - 10/\sqrt{Ft})}$$

   Where, Wir =15.13 for granite
   $$Wit = 15.13\ \frac{(10/\sqrt{804.10} - 10/\sqrt{1112.81})}{10/\sqrt{800.00} - 10/\sqrt{1193.32}}$$
   = 12.29 Kwh/ton

Appendix III

Table 1: Materials used for the development of new samples, C and D

Materials	%C	% Si	%Mn	%Cr	%S	%P	%Al	%Cu	%Mo	%Ni
Automotive Grey cast iron.	3.0- 3.2	1.2-1.9	0.5-0.6	-	0.05-0.1	-	-	-	-	-
Ferro Chromium	0.09	-	-	65.0	0.024	0.012	-	-	-	-
Ferro Molybdenum	0.16	-	-	-	0.025	0.025	-	-	65.5	
Nickel	-	-	-	-	-	-	-	-	-	99.9

Table 2: Percentage composition of the ferro alloys charged for the development of the new grinding plates as sample C and D respectively.

Element (%wt)	Fe-Cr	Ni	Fe-Mo
Sample C	2.0	3.4	-
Sample D	3.5	3.4	0.8

Appendix III





FIG 5: Sample of gold bearing Mineral sourced from Bagega. **FIG 6: Grinding in progess.**





FIG.7: Grinding in process.



FIG. 8: Show a failed sample plate.



FIG 9: coupling of grinding plates to the grinding media

FIG 10: ready to work



Fig 11: worn out plate after grinding



Fig.12: Powdered mineral ready for further processing

S/No	Type of Equipment	Location of the Equipment	Manufacturer	Quantity
1	Brinell hardness machine	Metallurgical and Materials Eng. Lab. ABU	Brooks Ind Ltd, Uk.Model CRBD	1
2	Impact testing machine	Mechanical Engineering Lab. ABU	Hoopman Ind Ltd, Uk.	1
3	Rotary Furnace	Artillery Barracks, Kaduna	Artillery Tech, Nig. Ltd	1
4	Grinding & polishing Machine	Metallurgical and Materials Eng. Lab. ABU	John Halt Ltd, Uk	2
5	Metallurgical Microscope	Metallurgical and Materials Eng. Lab. ABU	Benhosre Intl, Germany.	2
6	Energy Dispersive X-ray Flourence machine (ED-XRF)	NMDC, Jos, Plateau state.	Light house Ind. Ltd, Uk.	1
7	Optical Emmision Spectroscopic machine	DICON, Kaduna, Kaduna State.	Cophen Ind. Ltd,USA,	2
8	Electronic Weighing balance	Bagega Mineral Industries.	Bruce Ind, Ltd, Uk.	1
9	Attrition	Bagega Mineral	Deniver group	1

	grinding Machine	Industries	of Coy, Germany, Model A1	
10	Lab. Jaw Crusher serial No. BDA 15571	NMDC, Jos, Plateau state.	Joy, Manufacturing Co. Uk.	1
11	Cone Crusher serial No. 003	NMDC, Jos, Plateau state.	Deniver Equip.Co. Uk	1
12	Rolling Crusher serial No. B7141	NMDC, Jos, Plateau state.	Deniver Equip.Co. Uk	1
13	Ball Milling machine, serial No.69012	NMDC, Jos, Plateau state	Sprecher & Schuh Ind. Control, USA.	1
14	Automatic sieving machine	NMDC, Jos, Plateau state	Deniver Endecote Industries USA.	1

The equipment used for this work include rotary furnace, brinnell hardness testing machine of model CRBD manufactured by Brooks, impact testing machine, Grinding and Polishing machine, Metallurgical microscope, Energy Dispersive X-ray Fluoresce Machine (ED-XRF), Optical Emission Spectroscopic machine (OES). Weighing balance and Attrition grinding machine model A1 Deniver, 2009.

Laboratory Denver Jaw Crusher, serial no: BDA 15571 Sieze 6'-6", Type A. produced by Joy Manufacturing Co (Uk). Cone Crusher, (003) size 12, made by Denver Equipment. Deco Roll Crusher, Serial no:B 7141A(7-9-69). Bico Ball Milling Machine. Serial no: 69012. Manufactured by Sprecher & Schuh Industrial Control USA and Set of Screen ranging from +1400µm to -63 µm of Denver Endecot Automatic Test sieve shaker. Serial no: EFL 2mk 11(5471). Made by Endecot Industries Ltd Sw 19 Lo