INVESTIGATION OF HARDNESS AND IMPACT CHARACTERISTICS OF QUENCHED AND COLD TREATED DUCTILE CAST IRON

BY

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CERTIFICATION

This thesis entitled: investigation of hardness and impact characteristics of quenched and cold treated ductile cast iron. **By Terver Ause**, Meets the regulations governing the award of the degree of Master of Science (Engineering) of Ahmadu Bello University, Zaria, Nigeria and is approved for its contribution to knowledge for research activities.

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Head of Department Date

DECLARATION

I hereby declare that this thesis titled "Investigation of hardness and impact Characteristics of quenched and cold treated ductile cast iron" contains the report of my research work and has not been presented/accepted in any previous application for higher degree. Information from other sources has been acknowledged by means of reference.

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AUSE TERVER **DATE**

DEDICATION

This work is dedicated to my daughter Miss Faith Doofan Ause.

ACKNOWLEDGEMENT

Since education itself starts right at home and continues immediately thereafter, I wish to start by saying that; it is the view of Jesus Christ that we should give to Caesar what is Caesar's and give to God what is God's (Luke 20:25). In this respect, I wish to express my sincere thanks and outmost appreciation to my brothers Sabastine, s. Tegh (A.S.P) and Mr. Michael Anande Ityav for their kind assistance (morally and financially) right from my youth to grow up to be what I am today and whatever I shall be in future.

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ABSTRACT

The effect of austentitizing temperature and quenching medium on ductile cast iron in the as-quenched, cold treated and tempered condition was investigated. The study was based mainly on hardness and impact tests. Ductile cast iron speciemens were first given a normalizing beat treatment before quenching. Normalized specimens were heated to five austentising temperatures (800, 850, 900, 950 and 1000°C), soaked for one hour and quenched in three media (water, brine and ice-water). Some of the specimens were immediately subjected to hardness and impact test in the as-quenched and tempered conditions while others were immediately subjected to cold treatment at 20°C for two weeks in a domestic deep freezer after which hardness and impact tests were conducted in both old and cold treated and tempered conditions. The result shows that, ductile cast iron responded well to hardening in the three media. However, ice-water gave the highest severity of quench for all the austentitizing temperature used. Specimens quenched from 950^{o}C in ice-water, brine and water had the highest hardness values of 511,490 and 480 HB respectively. Optimum hardening temperature for the ductile cast iron was found to be between 900 - 950°C, while optimum tempering temperature for adequate hardness for wear resistance was found to be between 250 - 300°C then for strength and toughness it was found to be between 350 - 400°C.

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CHAPTER ONE

I.0 INTRODUCTION

Although the manufacture of cast iron generally has been an old process which has been going on over the ages, a new remarkable development is the discovery of methods to produce high strength cast iron at a minimal cost with high ductility that can be bent without breaking. This iron is commonly referred to as ductile cast iron because of its outstanding ductility and is also referred to as nodular cast iron because of it outstanding ductility and is also referred to as nodular cast iron because of spherical shape of the graphite found in the Microstructure (Elliotte, 1988). Prior to the discovery and production of ductile cast iron, most engineering applications involving the use of ferrous casting were limited only to steel, grey, malleable and white cast irons (Scully, 1975).

In those days, white cast iron was widely used because of high hardness which resulted from a martenstie due to alloying with chromium. The use of this white cast iron was expanding nicely during the period, but shortly after the U.S. Enter World War II, It became clear that certain crucial materials were becoming alarmingly scarce, and chromium was found to be one of them, hence, there was that fear that a possible curtailment of white cast iron production might occur in future, because without chroium, white cast iron will be less carbidic thus resulting to poor mechanical properties.

But iron was of great use that time in the war efforts, consequently, the U.S. government instructed the research laboratory under international Nickel Co. Ltd. to find a close substitute for chromium as carbide former in white cast iron. The condition was that, such an element must be abundant in nature, must be non-critical to the war effort and must be required in small amount. All the metallic and semi-metallic elements which were known to combine chemically with carbon to form carbide were, tested. It was found, (Millis et al, 1972), that addition of 0.5% magnesium gave a good starting efefect by increase the chill depth of the cast iron and exhibit unusual toughness by

resisting fracture.

It was further reported, (Mills et al, 1972) that chemical and microstructure analysis of the cast iron containing Magnesium surprisingly revealed that the graphite was not present as flakes, but as nodules well dispersed in the matrix, a structure never seen before in as cast grey iron. On 17th May, 1984 the break through in the development of nodular cast iron was announced during an annual general meeting held by the America Fundrymen's Association at Philadelphia, Pennsylvania where H. Morrogh or the British Cast iron Association announced that: Graphite in hypereutectic grey iron was induced to take the nodular shape by small addition of cerium. In the same meeting the work of Millis, Gagnebin and Pilling of USA was also disclosed. They too, achieved the same result though the addition of Magnesium to molten Iron. This led to the discovery of nodular cast iron production by the Magnesium and cerium processes.

Nouular cast iron, also known as ductile cast iron is an engineering material that has gained prominence in technological development, (Reynolds, et al, 1955). It is a type of cast iron in which the eutectic graphite is present in forms of tiny nodules, and for which it has the significantly unique mechanical properties. Presently, nodular cast iron is used mostly either in the as cast or fully heat treated condition. It has been shown, (Reynolds et al, 1955) that a quenched and tempered nodular cast iron produced improved mechanical properties that are better than as cast.

In comparison with other materials, nodular cast iron competes well with other metals especially with cast steels and heat treated steels in Machine building, but inferior to steel forging.

It is significantly superior to malleable cast iron, which was its predecessor and has completely replaced and thrown it out of production due also to economic reasons. In addition, nodular cast iron possesses excellent castability, shock resistance and machinability of grey cast iron (Ming, 1993).

Since many machine components in service operate under different conditions of impact, tension, compression, fatigue and wear, ductile cast iron has been found to meet these requirements, and therefore can be used as

automotive components especially as Crankshafts, camshafts connecting rods, clutch plates, brake drums etc, Recently, quenched and tempered ductile cast iron is increasingly found in high strength and high toughened applications.

TO minimize service failure, heat treatment operation is carefully performed on ductile cast iron components before putting it into service. This is the main reason why this work looks at the possibilities of using the quenching and tempering methods of heat treatment improve the mechanical properties of nodular cast iron.

The basis of the work is that ductile cast iron of the same chemical composition was austenitised at various temperatures and quenched in oil (Dauda, 1995), but the resultant hardness was found to be low. Therefore, the aim of this work is to investigate the effect of other quenching media (water, brine and ice-water) on mechanical, properties (hardness and impact strength) of ductile cast iron at various austentitising temperatures. To accomplish this, comprehensive series of tests were carried out on ductile cast iron in hath as-cast, as-normalized, as-quenched, cold treated and tempered condition.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.10 GENERAL

Cast iron belongs to a family of ferrous metals which are intended to be cast into tile desired shape which may be subjected to subsequent heat treatment but which cannot be mechanically worked. However, unlike steel, cast iron has a substantial amount of a eutectic structure. Cast iron have been defined basically as an iron – carbon alloy in which the percentage carbon is greater than 2.1 and silicon content between 1 - 3% with eutectic solidification (Walton, 1971). Cast iron make excellent castings (Smith, 1981), because of combined advantages of low cost and excellent castabilily.

2.2.0 CLASSIFICATION OF CAST IRONS

Cast iron is divided into three broad classes based on the structure of the eutectic these classes are:-

(i) white cast iron
(ii) Malleable cast iron
(iii) Grey cast iron
(iv) Nodular or ductile cast iron

2.3.0 WHITE CAST IRON

2.3.1 STRUCTURES AND COMPOSITIONS

White cast iron derived its name from the fracture appearance because when a cast piece is broken, a white crystalline fracture surface is seen.

The general range of chemical composition of unalloyed white cast iron is given as: 1.8 - 3.6%C. 0.5 - 1.9%Si, 0.25 - 0.8%Mn, 0.06 - 0.20% S, 0.06 - 0.18% P, (Smith 1981). White cast iron that has been slowly cooled in the mold has a structure of pearlite and free cementite similar to that of high carbon steel except that the white cast iron contains much more free cementite in the microstructure.

2.3.2 PROPERTIES OF WHITE CAST IRON

White cast iron is very hard, brittle and virtually unmachineable. The mechanical properties of white cast iron are not as important as those for the nodular or even grey cast iron. The most significant property is the excellent resistance to wear and abrasion due to the presence of massive cementite in the microstructure. It also has high compressive strength with good retention of strength and hardness at elevated temperature.

2.3.3 AREAS OF APPLICATION OF WHITE CAST IRON

Bet()re the introduction of nodular cast iron in 1948, according to Millis (1972), the greatest tonnage of white cast iron was used for the manufacture of malleable cast iron through heat treatment. White cast iron is presently extensively used for making parts of machinery and industrial equipment where extreme hardness and wear resistance are required such as in crusher jaws and hammers, wearing plates, cams, grinding balls and liners for ball mills, parts for cement crushing, grains and ores, rolls for rolling mills, Farm implements, railroad car wheels (Elliotte, 1988); and diversified applications.

2.4.0 MALLEABLE CAST IRON

2.4.1 STRUCTURES AND COMPOSITION

The general range of chemical composition of a typical malleable cast iron is as follows:

2.0 - 2.5% C, 1.0 - 1.5% Si, 0.20 0 1% Mn, 0.04 - 0.18% S, 0.16%P maximum. There is need for higher silicon content in the white cast iron for production of malleaole cast irons. This is to enable easy breakdown of the cementite.

Malleaole cast iron is white cast iron that has been thermally treated so that it attains significant ductility (Budinski, 1979). It is made by the prolonged annealing process of the brittle white cast iron in a controlled

atmosphere furnace; thus converting the white iron to either a ferritic or pearlitic. During this process, the cementite is converted into austenite and graphite (in flower like shape) known as temper carhon.

Malleable cast iron is not malleahle as in the sense in which steel is Considered to be, (Dell. 1978), hut it does exhihit greater toughness and ductility when compared to other types of cast iron like -grey cast iron. However, malleable cast iron is softer than grey cast iron and exhibits easier machining characteristics.

2.4.2 PROPERTIES OF MALLEABLE CAST IRON

According to Bundinski (1979), most of the physical properties of malleable cast iron are similar to those of - grey cast iron however, the main differences are found in, the mechanical properties, one of which is the high ductility which makes it possible to bend the iron without breaking. It can also be loaded in tension and it can withstand impact loads.

Another important property of malleable cast iron is its high modulus of elasticity which makes it have good stiffness comparable to steels. It is also an extremely stable cast iron because of the long annealing heat treatment cycles. Wear characteristics are still high because of the temper carbon in the microstructure. Fatigue, tensile and compressive strengths are also high.

2.4.3 AREAS OF APPLICATION OF MALLEABLE CAST IRON

Because of the foregoing properties, malleable cast iron can be used extensively in areas where greater toughness and resistance to shock are required. Some of those typical areas of applications are: in agricultural implements for ploughs, tractor parts, harrow, cultivators, rakes, spreaders and poultry equipment.

Other areas include; automobile parts for wheels, spring assembly, brake drums, axles, steering, gear assembly and body accessories; it is used for machine tools like lathe machines, planers, grinders, gear cutters, drills and electric motor and generator parts. In the marine industry, it is used for making anchors and chains while in the railway system, it is used for the

construction of various parts of locomotive.

2.5.0 GREY CAST IRON

2.5.1 STRUCTURE

Grey cast irons solidify with austenite - graphite eutectic, but with graphite taking the shape of flakes. The microstructure is such that practically all of the carbon is present as free graphite flakes in the matrix of steel (Gulyaev, 1980). In general terms, the structure of cast iron differs from those of steels by the presence of graphite inclusions in the structures. In grey cast iron, graphite flakes nucleate from the melt and sometimes a portion of cementite dissociates into ferrite and graphite (Clark, et al, 1962). The matrix structure of - grey cast iron can be readily changed by heat treatment hut the graphite flakes, once formed cannot be changed by heat treatment, (Dell, 1978).

However, the quantity, shape and size of the graphite flakes may vary within a wide range. Based on the type of matrix, this iron could be grouped into:

(i) Pearlitic grey cast iron
(ii) Ferritic - pearlitic grey cast iron
(iii) Ferritic - grey cast iron
(iv) Pearlitic - ferritic grey cast iron.

2.5.2 CHEMICAL COMPOSITION

The basic composition of cast iron is usually described in terms of carbon and silicon contents. These are the two principal elements in unalloyed -grey cast irons. However, the presence of phosphorus (P) in addition to silicon (Si) plays significant roles in determining the mode of solidification and the eutectic content of the iron.

The eutectic composition for the fe - C system is 4.3%C, and is much lower in the presence of Si and P. For this purpose, carbon equivalence determines how near eutectic composition the melt is. When carbon

equivalence (C.E) is near the eutectic value, the liquid state persists to a relatively low temperature and solidification takes place over a small range. (Smith, 1981).

The carbon equivalence (C.E) of a melt is determined by:

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

Where TC = Total Carbon,

The melt is eutectic if C.E = 4.3%.

In general, the compositions of grey cast irons are near eutectic and in the unalloyed grades, have been given as:

2.5-4.0%C, 1.0-3.0%Si, 0.25-1.0 Mn, 0.02-0.25%S, 0.0S-1.0%P, Smith (1981).

In hypereutectic irons (C.E greater than 4.3%), there is a tendency for proeutectic graphite that forms and floats free in the molten iron to precipitate on solidification under normal cooling conditions. In hypereutectic irons, the lower the C.E, the greater the tendency for white iron to form on solidification.

Silicon is a very important element in grey cast iron. It exerts the greatest controlling effect on the relative proportion of combined and graphitic carbon. Generally, when the silicon content in a given cast iron is increased, a greater, proportion of graphite will be formed in the structure at the expense of cementite and this can serve as a means by which the properties of the iron can be controlled. By changing both the carbon and silicon content leads to wide variation of properties of cast irons. Generally, the amount of silicon in cast iron varies between 1 - 3 % (Gilbert, 1969). For instance, the strength of grey cast iron decreases with an increase in carbon or silicon content (ie carbon equivalence). High carbon content causes an increase in the amount of graphite formed, while an increase in the silicon content increases the ferrite content as well as more graphitization.

The amount of manganese usually found in cast iron varies between 0.4 and 1.0%, less than 1.0% has been found- to have very little effect upon the properties of tgaay - cast iron. With more than 1.2 % manganese, strength, hardness and resistance to wear are increased, whereas, the machinability is

decreased because of the greater stability of cementite.

The outstanding effect of phosphorus is to improve the fluidity of the cast iron. For high strength cast iron, it is desirable to maintain a low phosphorus content. Phosphorus in amount less than 0.3 % is dissolved in the ferrite of grey cast iron, but with more than this amount, a hard brittle compound called iron phosphide (Fe3P) is formed.

2.5.3 PROPERTIES OF GREY CAST IRON

The properties of Grey cast iron are determined both by the composition and the, matrix structure. Several properties are derived from the existence of flakes in the microstructure.

One of the outstanding properties of grey - cast iron is its high fluidity in the Molten state. It has been found (Walton, 1971) that of all ferrous metals, molten grey and ductile cast irons have the highest fluidity (longest liquid interval from casting temperature to (solidification) hence, they are particularly suited for the production of intricate and relatively thin-walled castings. Solidification shrinkage and solid contraction is also low, hence distortion of the cast production is eliminated. This offers the iron good manufacturing economy in respect of complex shapes.

Other properties include excellent vibrational damping capacity which depends on the quantity, shape and distribution of graphite flakes in the matrix. It is greatest in the soft matrix structure. (Ferrite).

Grey cast iron has high compressive strength with poor tensile strength (Walton, 1971), hence, is mainly applied for hearing loads in compression, for example, as in machine bed and engine block.

Grey cast iron also has good resistance to thermal shock and corrosion. The strength values are generally low for all grades and are extremely brittle. The strength of this cast iron depends on the matrix structure, being higher for increased pearlite content.

2.5.4 APPLICATIONS OF GREY CAST IRON

Grey cast iron is widely used for general engineering applications, typical

among which include: Fresh water pipes and sewage pipes because it resist corrosion in alkalis, it has a standard material of construction for pipes and fittings for portable water, (Budinski, 1979). The iron is also used for making automotive engine blocks, machine beds. cylinder heads, clutch (pressure) plates, brake drums, gear cases, car wheels, flywheels, household appliances, electric motor frames and agricultural implements.

2.6.0 DUCTILE OR NODULAR CAST IRON

2.6.1 STRUCTURE

Nodular cast iron consists of graphite in nodular form well dispersed in a steel matrix. - These nodules have a minimum influence on properties of the Iron (Dell, t 1978), while tile mechanical properties are greatly influenced by steel matrix surrounding the graphite nodules. Typical matrix structures found in nodular cast iron are:

Ferritic, pearlitic and martensitic; and are responsible for the wide range of properties obtained.

In the as cast condition, the microstructure consists of graphite nodules which are surrounded by free ferrite in a matrix of pearlite, (Smith, 1981) giving what is known as the Bull's eye structure. The greatest advantage offered by this iron over the, rest of cast irons is the absence of excessive brittleness of grey and white irons, higher tensile strength and toughness.

2.6.2 PROPERTIES OF DUCTILE CAST IRON

Ductile cast iron combine the good process properties of cast iron with good engineering/mechanical properties of steel, these properties include: excellent castability due to low melting point, high rigidity, low shrinkage on solidification and cooling, good machinability, wear resistance, high strength, toughness, ductility, hardenability, good impact and shock resistance.

2.6.3 APPLICATION OF DUCTILE CAST IRON

According to Scully (1975), ductile cast iron has had an outstanding usage as high-pressure pipes in the past decade, but in recent times the automotive industry and power generation are the major consumer of ductile cast iron. Power generating sets especially the internal combustion engines such as the gas turbine, etc. have ductile iron components that include crankshaft, engine block with cylinder head, connecting rods, turbocharger casing, main bearing caps and exhaust manifolds.

The use of ductile cast iron for power transmission components is extensive, the main area being for those in the private and passenger cars. Some of the engine parts that could be made using ductile cast iron include: Clutch plates, differential and pinion housings, back axles and wheel hubs, heavy duty rear axle. According to Scully (1975), one new innovation was the adoption of nodular cast iron for the yoke pieces of a universal joint coupling for the power takes off for tractor and commercial vehicles in place of steel forgings.

Other typical areas of application of ductile cast iron include brake drums, knuckles, wheel support mechanisms, transmission gears, engine blocks, pistons requiring wear resistance and strength, roller gears for farm machinery, hollow automotive crankshaft and diesel engine connecting rod.

2.7.0 PRODUCTION OF DUCTILE IRON CASTINGS

Two processes of producing ductile iron castings were discovered independently and announced in 1948 (Millis et al, 1972). These were:

(i) The British cast iron Research Association (BCIRA) process which consists of an addition of cerium to molten hypereutectic cast irons of essentially the same analysis as grey iron, and

(ii) The U.S.A international nickel company (INCO) process which employs magnesium additions to either hypo or hypereutectic ease-irons.

The key to the production of ductile iron castings is the spheroidizing or nodulizing of the graphite by small but significant percentages of retained cerium and magnesium in the liquid iron before solidification. According to

Millis et al, (1972), while other elements like cerium, calcium, lithium, sodium, etc displays similar characteristics and promote nodular graphite, magnesium process is so far the simplest and most economical method of producing ductile iron castings. Although the mechanism by which magnesium causes graphite nodules to occur is unknown, however, the function of magnesium additions is well known (Heine et al, 1972).

Ductile cast iron is made by the addition of small amount of magnesium (0.01- 0.10%) usually in form of ferroalloy into a ladle of molten iron, this addition causes a vigorous mixing reaction resulting to formation of graphite nodules which are uniformly distributed in the structure when the iron solidifies. (Clark et al, 1962}. The molten iron could also be treated with only cerium in the Ladle or combination of cerium and magnesium to obtain the graphite in form of nodules. In most commercial applications, both magnesium and cerium are used, but cerium in very small quantities has been reported (Morrogh, .1952) to greatly reduce the sensitivity of the magnesium process to elements such as lead, bismuth, antimony, tin and Titanium which inhibit the formation of nodules in a melt.

2.7.1 MAGNESIUM TREATMENT OF MOLTEN IRON

In addition to magnesium being a good nodulizing element, it also serves as a deoxidizer and desulphurizer of molten iron. The amount of magnesium required to produce nodular graphite is dependent largely on the sulphur and oxygen content of the base molten iron. If the oxygen and sulphur content of the melt is too high, a substantial amount of magnesium will be consumed in the formation of magnesium oxides and sulphides which are stable, has low solubility in the melt and thus floats to the surface and can and should be removed. According to Lalich (1974), general minimum retained magnesium content of about 0.015-0.050% is considered adequate.

Addition or magnesium in a form of pure metal is very hazardous due to its reactive nature. To reduce the volatility or the reaction magnesium is usually alloyed with other elements to form alloys like:- Magnesium - Ferrosilicon with a typical composition of:

9%mg, 45%si, 1.5% Ca. balance Fe (Heine et al, 1967).

Magnesium recovery in the melt is dependent on the method by which magnesium - Ferrosilicon alloys are added to the melt. The most common methods of adding magnesium to molten iron for nodulizing are, the open ladle method, the plunging method, and the mechanical feeder method as described below (Matter, 1975).

2.7.2 THE OPEN LADLE METHOD

This method consists of first placing the magnesium ferro-alloy on the bottom of an open, pre-heated Ladle, and then liquid iron is poured onto the alloy as rapidly as possible. These treatments Ladles are designed to be deep and narrow, having a height to diameter ratio of 2:1 as shown in figure 2.1. The violent reaction of magnesium vapour with the liquid iron is therefore confined to the ladle. The reaction of the liquid iron with magnesium produce' a dross containing magnesium sulphide and oxide which floats to the surface and is then removed as slag.

Since the open-ladle magnesium treatment method was found to be inefficient, several improvements on it have been suggested (Karsay, 1979). The most commonly used modification is known as the "sandwich" method. This method is a direct descendant of the open ladle process, retaining its basic ladle configuration and its process advantage of simplicity. The principal difference lies in the bottom design wherein a pocket is provided to hold the treatment alloy and cover material as shown in figure 2.2. In this manner, when the liquid iron is tapped into the ladle, the reaction time is delayed until the ladle is at least partially filled with metal, thus increasing the magnesium recovery to a considerable level.

2.7.3 THE PLUNGING METHOD

As shown in figure 2.3. in this plunging method, a refractory bell containing the A nodulizer is submerged deeply into a ladle of molten-iron. The nodulizer is thus prevented from floating hence improving recovery. The hell is provided with holes through which the evolving magnesium and the liquid iron

intermingle.

2.7.4 MECHANICAL FEEDER METHOD

This method of nodulizing makes use of a mechanical feeder whereby the magnesium in a form of ferror-alloy is continuously added to the melt stream emitting from the furnace into the Ladle. This method permits continuous and uniform treatment of the melt at generally greater magnesium recoveries.

According to Ashton and Alt (1972), another technique have been developed permitting the use of metallic magnesium. In this method, magnesium metal is added either by a plunging technique in a covered ladle under several atmospheres of pressure or by injection through a refractory tube into the melt using an inert gas as a carrier.

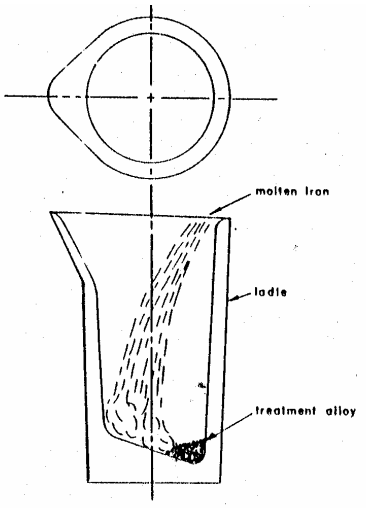


Fig.2.1 - Schematic of the open ladle transfer method for treating ductile iron.

SOURCE: SOURCE BOOK ON DUCTILE CAST IRON (1975).

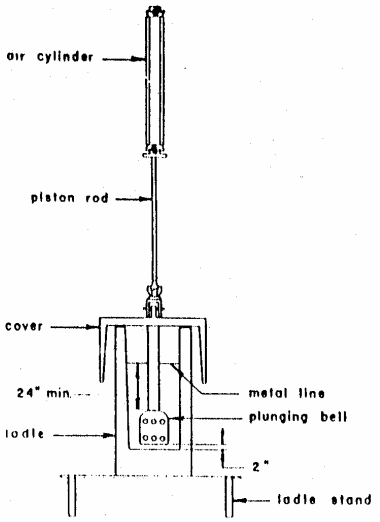


Fig.2.3 - Schematic of plunging method for treating ductile iron.

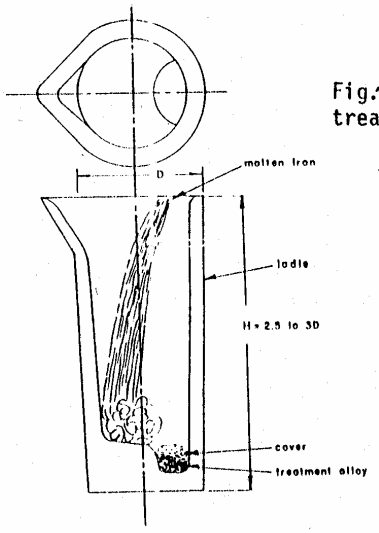


Fig.2.2 - Schematic of sandwich method for treating ductile iron.

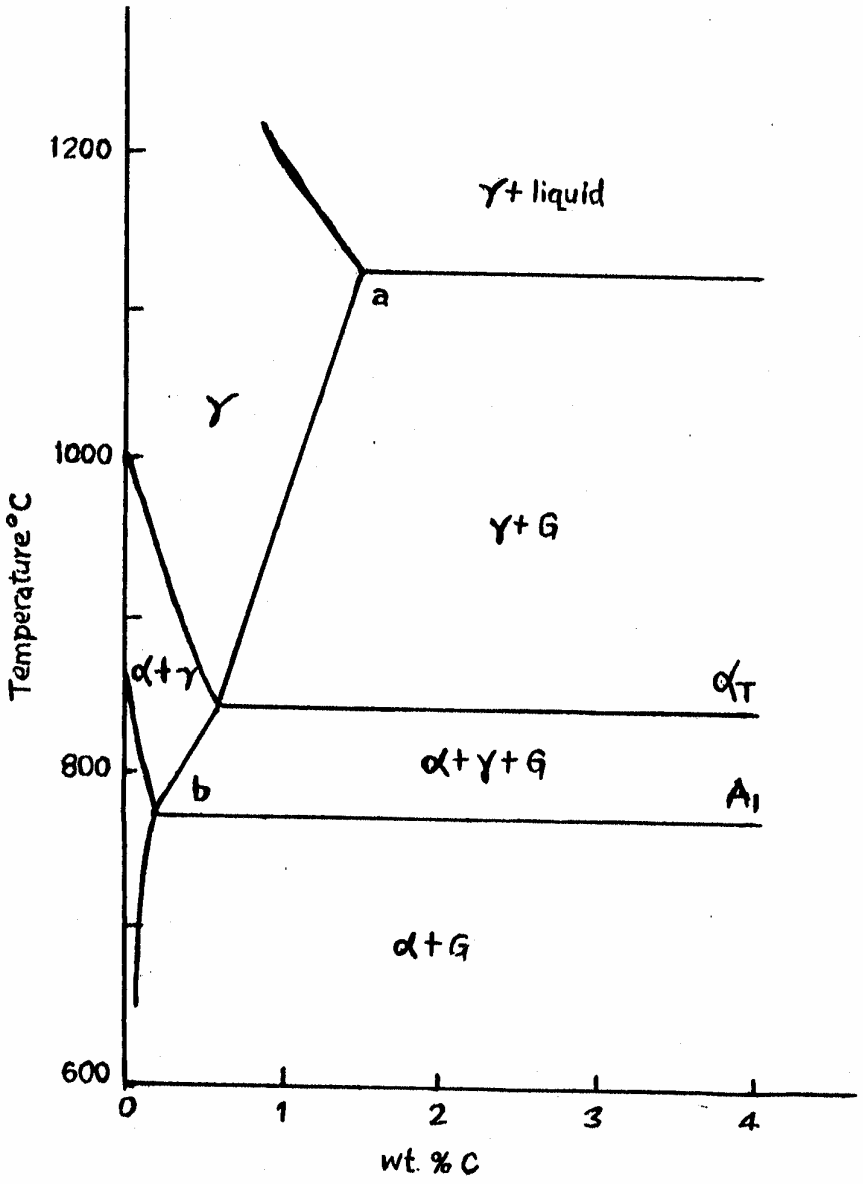


Figure 2.4. Section of the Fe-G-Si phase diagram at 2% Si.
SOURCE: ELLIOTTE (1988).

2.7.5 INOCULATION

Although the magnesium treatment is responsible for the development of graphite nodules, quality ductile iron casting also requires the use of an inoculant. Effective inoculation (Post inoculation) is therefore mandatory for production of high quality ductile irons.

Inoculation is the practice of adding terror-alloys to the melt to help increase the number of graphite nodules (eutectic cells) during solidification and to minimize the formation of carbide, Vernon (1975). Since the eutectic carbide when formed, results in greater hardness and general inferior mechanical properties, ensuring their elimination by inoculation has become a standard practice. According to Watton (1971), inoculants in general, may affect the nucleation and growth mechanism in two major ways:

(i) They may provide a suhstrate for nucleation (an artificial embryo effect) and

(ii) Alter the phase equilibrium.

The most effective inoculants used for ductile iron are the ferro silicon alloys (Heine et al, 1967). These alloys are produced in a variety of grades, but the most widely used grade is the 85% Si. Inoculation is done by reladling the magnesium treated iron onto terror-silicon placed in the bottom of the ladle, alternatively, the terror-silicon alloy is added to the metal stream during reladling.

Recent studies have also shown (Remondino, 1974) that a very small amount of ferro-silicon can he added to the sprue or runner system during the pouring of the mold when it is necessary to ensure that no eutectic carbide is formed during solidification.

2.8.0 HEAT TREATMENT OF DUCTILE IRON CASTINIGS

2.8.1 GENERAL

All the heat treatment processes that apply to carbon steels also apply to all cast irons especially the ductile irons. The basis for the various heat treating cycles is the equilibrium diagram and the TTT curves (Budinski, 1979). But hecause ductile cast iron contain higher silicon, the normal Fe-C phase diagram is not strictly applicable., The following modifications are

necessary to be appreciated as shown on the Fe -G - Si. Phase diagram at 2% Si in figure 2.4. ,

Hardening and softening of tile matrix structures hy heat treatment are reversible processes. However, the shape and distribution of the graphite in iron cannot be changed by heat treatment; this is because, once the graphite has I()rmed during ", 111 solidification, its shape and distribution cannot be altered in the solid state through heat {

The heat treatment processes applicahle to ductile cast iron include: Stress relief, ~I ferritizing anneal, normalizing, quench hardening, and tempering. Others are surface hardening treatment hy flame anQ induction hardening, austempering and ,. . ~ martemperlng.

2.8.2 STRESS RELIEF

The Inost common causes of internal stresses in castings are, nonuniform cooling ()f different sections as a result of different section sizes or presence of chills in the m()ulds. The 11()tter sect«)ns ()f the casting continues u) contract ()n c()oling, wllile the .~"" "."-"... ""'- cooler sections have cooled to the room temperature resisting the contraction of the t()rmer. This result in the cooler parts of the casting heing suhjected to compressive stresses while the

already cooled parts are put in tens«>n. If the tensile stresses are sufficiently high, fracture may occur in the casting. It is theret()re very important that castings should he uniformly cooled to minimize the internal stress level.

To remove stresses, a stress relieving heat treatment is carried out at sub-critical temperatures sufficiently high enough to remove the stresses but not so high to modify the general microstructure as well as the ll1echanical pr()perties (Gilhert, 1969). As a general rule stress relief treatment should not change the Microstructure.

Cooling of castings, especially of complicated shapes in the mould is not always unil()rm, internal stresses usually develop. According to Gilhert (1969), these 1 stresses will J1()t occur until cooling is helc)w ahout 600°C He t()und out th~tt, at higher temperatures, internal stresses created due to differential cooling rates in the different sections are relieved automatically.

2.8.3 ANNI~ALINl;

III the hroad sense. the term anllealing means softening. Steels and cast irons are usually suhjected to annealing. The annealing process is perf()rmed either u) illlprove machinability or hardenahility of a steel.

Ductile cast irons usually have pearlitic or ferritic -pearlitic structures in the as - cast condition and annealing heat treatn1ellts are carried out to remove or reduce the pearlite content to an acceptable level. Ferrite matrix structures are much softer and 111()re ductile than pearlitic structures. If' undesirahle f'ree cementite is present in the as -cast structures, it can also be eliminated during an annealing heat treatment provided heating to the austenite region is done. Castu1g stresses can be eliminated by an annealing treatment provided the castings are slowly cooled after heating.

The annealing of ductile cast iron is a two stage Ileat treatment process (Gilbert, 1969). In the first stage the casting is heated above the critical temperature range to dissolve all primary carbides into the austenite and soaked for the desirecl length of time. The second state can he accolnplished by either:

(i) fumance cooling down to 690°C, soaked for some time then cooled uniformly to room temperature or

(ii) Furnace cool- slowly at a rate of 2°C/hr between 690 - 650°C then . cool-uniformly to room temperature.

2,8,4 NORMALIZIN(;

Normalizing treatment is usually understood to involve the heating of castings for a peri()d in the austenite range followed hy cooling .in the air. In steel castings, normalizing treatment is usually done to produce grain refInement as a pre-hardel'ling condition. It removes unfavorable structures such as widmanstatten and cementite

network present in the as -cast compollent. This treatment usually gives a pearlitic structure which is finer and more uniform than that present in the as-cast condition so that an increase in strength is obtained.

Ductile iron castings are given a normalizing treatment usually to eliminate tree carhides and to obtain a homogenous structure of fine pearlite. The treatment is usually done by heating the castings to temperature range of 850 -900°C, soaked for one hour per inch of section thickness and air cool (Gilbert, 1969). The cooling rate will depend on the mass of the casting, but it may be influenced also by the temperature and ~! movement of the surrounding air. .. ,

Normalizing is commonly t()llowed by tempering to reduce hardness and to , , relieve residual stresses that developed when various parts of the casting were cooled. I '. The effect of tempering on the hardness and tensile properties depends on the i"': " ~ composition of the iron and on the hardness level that was obtained in nom1alizing. In l' J general, peatlitic structures from normalizing softens less than the harder martensitic ,~ structures that are obtained by quenching.

Alloying elements also have an important function in nodular cast irons that are to be normalized. According to Reynolds ~ ~ (1955), moderate additions of alloying elements increase hardenability sufficiently so that a microstructure of fine pearlite may be obtained in normalized castings with sections up to 6 inches thick. According to them Nickel is preferred as an alloying element because it strengthens the iron in all section thicknesses and does not t()ml carbides. Molybdenium, in combination with

nickel is effective in increasing hardness and strength.

2.8.5 HARDENING OF DUCTLE CAST IRON ! ~

Ductile cast iron is commonly used in the hardened condition since wear h I resistance is. one .Of the most important characteristics The ~ctual hardne~s obta~ned rafter hardemng wlll depend on the structure of the cast Iron prIor to quenchIng. ThIS IS i i with respect to composition and homogenization of the prior austenite (Walton, 1971).

The properties of the hardened cast iron is influenced by the following:

(i) Composition and grain size (ii) Hardening temperature

(iii) Quenching procedure and cooling rate (Elliotte, .1988)

All these t'actors are critical to the hardening characteristics of ductile cast iron to produce martensite. Martensite- accordil1g to Wilson (\ 975) promotes high .llardness and good wear resistance but retained austenite reduces them.

All cast irons including ductile cast irol1 can be hardel1ed by heating into the , austenite range followed by quenching in the desired medium. On heating up to a temperature such as 850 -950°C in the austenite region, carbon is rapidly absorbed froll1 the graphite modules and the carbol1 contel1t of the matrix increases as the austenitizing temperature is increased (Gilbert, .1969). On quenching, a high carbon content is retained and a hard brittle martensitic matrix structure is produced. The

maximum hardening temperature normally corresponds to that at which full homogenization of austenite is achieved. The hardening temperature of nodular cast iron will influence the structure and composition of austenite before quenching.

Heating ductile iron to higher temperatures in excess of 950°C results in the formation of coarse grain structure in the prior austenite and leads to high retained i austenite, dimensional instability and sometimes cracks. On the other hand, low austenitizing temperatures such as 800~C causes poor homogenization hence low hardened properties because the casting is not fully austenitized due to the presence of silicon in the iron in appreciable amount which raises the critical range up. This means r! 11 ~ higher temperatures are needed to get the iron fully austenitized.

Oauda (1995) worked on ductile cast iron hy austenitizing at various temperatures then quenched in oil; the resultant hardness was found to he low as shown in table 2. 1 .

Table 2.1: Hardness values (HB) of specimens quenched in oil at various temperatures. Source: Oauda, E. T. (1995). '

Quenching Temperature (C)	Medium (oil)
750	162
800	172
850	247
900	400
950	400

2.8.6 'rEMPERING

Tempering is the final stage in hardening. It employs moderate reheating to modify or alleviate the extreme hardness of martensite and bring about a controlled degree of softetlitlg by producing tempered Martensite (Raj.\tl ~ f\l, 1988). Tempering of quench -hardenable steels and cast irons is a must and is done "to achieve various objectives. Tempering generally is done primarily to relieve the internal stresses generated during quenching and to maintain, structural and dimensional stability for a maximum attainable hardness. To achieve these, tempered martensite is formed and anyi ! retained austenite present must be transformed (Lament ~ f\l, 1953).

Tempering is done usually by reheating the hardened ferrous component below the lower critic.tl temperature, followed by cooling in air or at any desired rate. Tempering ll)wers hardness. strength and wear resistance marginally. H()wever. this marginal loss is adequately compensated by advantages gained by relieving of internal stresses, restoration of ductility and toughness, and transf~)rmatil)n of retained austenite.

The higher the tempering temperature, the more is the restored ductility and the tougher the component. Tempering at low temperature will not cause austenite transformation. However. tempering at higher temperatures will cause the prior martensite to temper and soften even before austenite transformation occurs.

CHAIYfER THREE

.-:0-.. 3.(EXPERIMENT AL PROCEDURE

3.1.(t INrrRODucrnON

The aim of this work is to investigate the mechanical properties of hardened ductile cast irons. In this work, effect of hardening temperature and cooling medium on the hardness and impact values of nodular cast iron was investigated.

3.2.0 METHODOLOGY ~

Tests were carried out on ductile cast iron bars that were hardened by quenching ! in dit'terent media. Hardness values were measured in hoth the as-quenched condition and as refrigerated conditi()n. Tempering of both samples in both conditi()n was u()ne.then ilnpact test was conducted; the micrographs were also taken

In order to obtain good reslllts, some reasonable control of the experimental process and part\meters Wt\S importt\nt. The following met\sures were tt\ken.

1. All heat treatment operations were carried out in a carbolite muffle
2. All the test pieces to he heat treated were packed in carhurizing media which consisted of cast iron chips mixed with pulverized charcoal
3. Heating of the ductile cast iron test pieces for austenitizing was done first by heating to 6500C at the normal heating rate of the furnace and soaked for ten minutes. Final heating to the required austenitizing temperature t was rapid and soaking at the desired temperature for one hour followed

this. Discharging of the austenitized specimens into the quenching media ,was done very fast with minimum loss of temperature.

4. All the test pieces were given a pre-hardening treatment (normalizing) by heating to 95lfc, soaked for one hour and then cooied in air.

5. Specimens for hardness measurements were prepared by wet grinding of the surface to a final. Smoothness on 600grit paper. Hardness measurement was conducted using a brinell hat-dness tester. Three different hardness measurements were carried out on each test piece and the average result obtained. It is important to note here that this investigation involved a lot of hardness measurements. About 110 specimens were tested fl)r hardness. In addition, due to breakdown of the hardness tester in the departmental laboratory, many trips were made to National Metallurgical Development Centre (NMDC), Jos to carry out the tests. -

6. Some selected specimens were taken and prepared for icrosfructural observation. The following metallographic structures were of interest:

   (a) As -received

   (0) As -normalized

   (c) As -quenched

   (d) As -tempered

The results (Micrographs) are shown on plates 4.1 to 4.5. ,

Metallographic preparation ()f the specimens was done by successive fin'. during grinding, water was added to ensure adequate cooling of the specimens. After the grinding was completed, the specimens were rinsed in water before polishing.

Polishing was carried out on a rotating whee! using nylon cloth and one-micron aluminium powder. The surface of each sample was cleaned with cotton wool soaked in alcohol and etched with 2 % Nitric acid in alcohol (Nital) for thirty seconds. The specimen was then rinsed in alcohol to stop the reaction of Nital. and then dried in air. The etched specimens were placed under the metallurgical micr(}scope. the microstructure was viewed and the micrographs were taken, the film was removed, developed and printed.

7. Avery Denison impact testing machine with the capacity of 120 foot pounds (J) was used to conduct Izod impact tests.

3.3.() MATERIALS

Test specimen of ductile cast iron measuring 56mm in length by lOx 10mm cross sectional area were used for the tests. These specimen were imported trom U.S.A and .-made avail,thle for the experimental investigation by the assistance of Dr.

J.O.T. Adewara. The specimen were obtained in the as-cast condition. The chemica\ ,osition of the ductile cast iron is shown in Table 3.1.

Table 3.1 Chemical Composition of As-received ductile cast iron

CHEMICAL COMPOSITION								
C	Mn	Si	Cr	S	P	Mg	Ni	Fe
3.63	0.36	2.26	0.07	0.01	0.03	0.01	0.05	Balance

Three quenching media were prepared in three p\astic buckets and they were:

(i) Water

(ii) Brine Solution

(iii) Ice water

3.4.0 EPERIMEN1'AL DETAILS

3.4.1 AS-NORMALIZED PROPERTIES

Al\ the ductile cast iron specimens to be quenched were given a prehardening treatment hy nonna\izing. Appendix \ shoW the results of hardness and impact test of as-received and normalized specimens.

3.4.2 AS-QUENCHED PROPERTIES

Five fireclay ceramic crucibles were se\ected. This is hecause five austenitizing thardenlng) temperatures were to he used. \n each crucihle, \2

specimens were packed with cast- iron dips and pulverized charcoal. The crucibles: '. were covered and sealed with clay before being loaded into an electrically heated , muffle fllrnace and progressively heated to selected austeni4zittg temperatt[res of i ~ \ 800. 850. 900. 950 and lOOOoC. When this was attained. it was allowed to soak for ~ " 2 " !' one hour. Then, at each austenitizing temperature. the contents of one crucible <. 12 specimens) were removed and specimens quenched in each of water, brine and ice water. Of the t{)l[r specimens t{)r each medium one is for:

(a) Direct hardness test after quenching

(b) Hardness test after posts hardening cold treatment t'or two weeks at -2a)C in 'a I~ II I' d()mestic deep treezer. :

(C) [mpact test after quenching !'

(d) Impact test after cold treatment at -laIC t()r two weeks. ~

The results obtained are sh()wn in tigures 4.1 t() 4.4.

3.4.3 QUENCHED AND TEMPERED PROPERTIES

Another three rcrl[cibles were selected. In each of them. 31 specimens were kept. The content of one crucible was quenched in one medium whereby a set of eight specimens were for:

(a) Inlmediate tempering at 150.200.250.300,350.400.450, and 5()()"C tc)llowed by hardness test.

(b) Tempering after cold treatment 'for two weeks and measuring as tempered

hardness. """

(c) Tenlpering immediately after quenching followed by impact test of the tempered specImens.

(d) Tempering the cold treated specimens followed by impact test.

The three crucibles with the c()ntent were sealed and loaded into the furnace and heated progressively to 95otJC and soaked for one hour. They were removed and the content of each quenched in water. brine and ice water. Sixteen specimens were : , I tempered immediately and hardness and impact test conducted. The remaining sixteen I I, specimens were subjected to cold treatment at -20°C in a domestic deep freezer for two I .I~I " .. weeks. After which they were removed. tempered and hardness and Impact tests l: , c(}ndllcted. The reslllts are shown in Appendices 8 -II and figllres 4.5. 4.6. 4.7 and ~ .8.

CHAPTER FOUR

4.0 RESULT AND DISDUSSION

4.1.0 RESUI..I T

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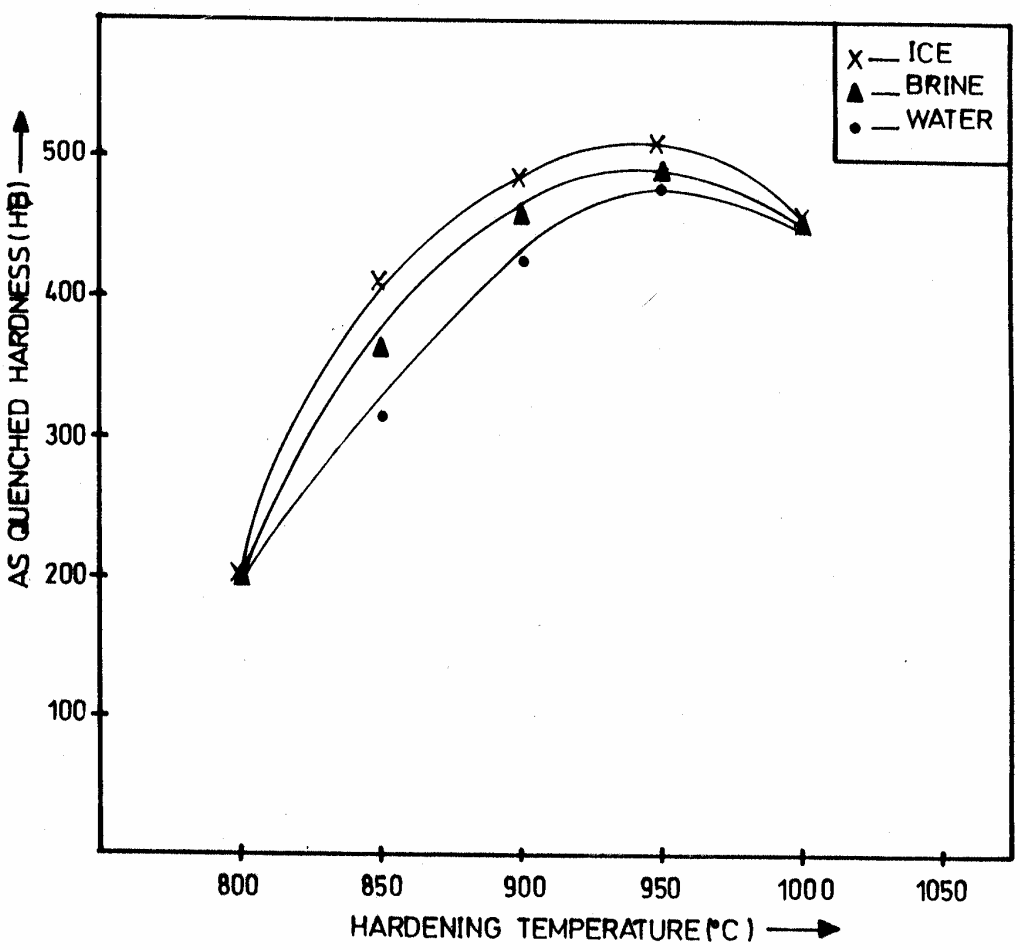
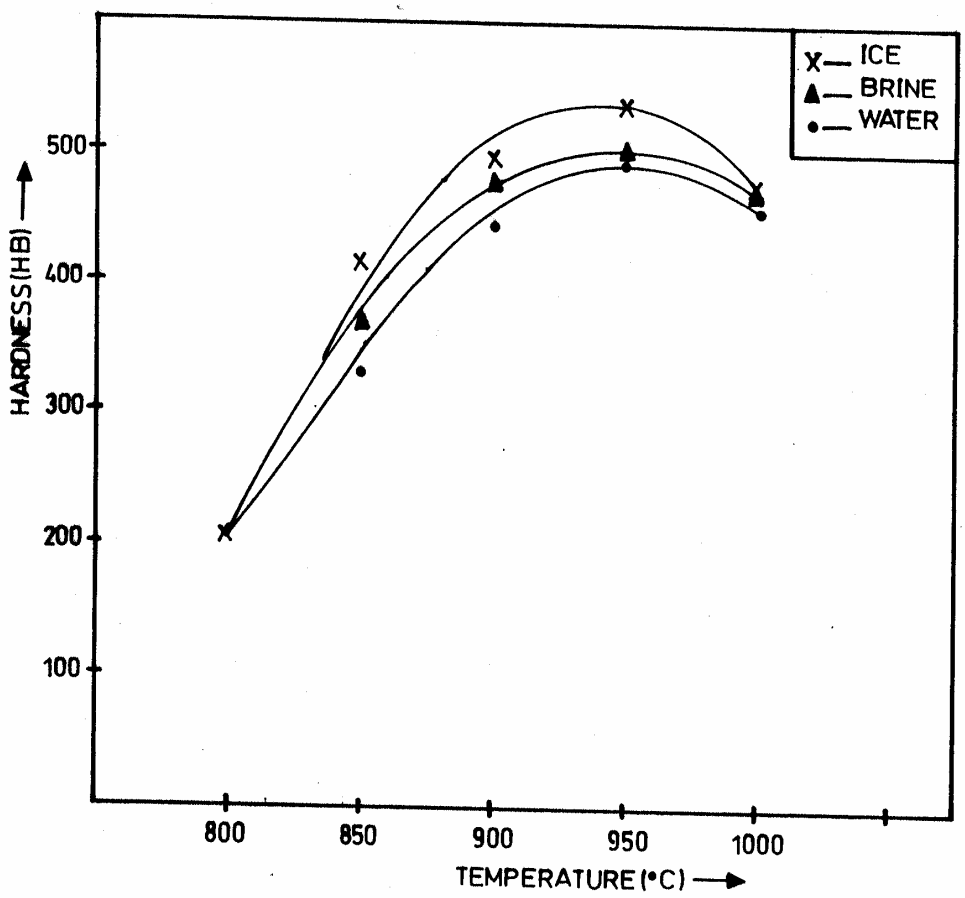


FIG.4.1. EFFECT OF HARDENING TEMP. AND MEDIUM ON THE HARDNESS(HB) OF SPECIMENS QUENCHED IN WATER, BRINE AND ICE.



4.2. EFFECT OF HARDENING TEMP. AND MEDIUM ON THE HARDNESS(HB) OF SPECIMENS QUENCHED IN WATER, BRINE AND ICE THEN COLD TREATED FOR TWO WEEKS.

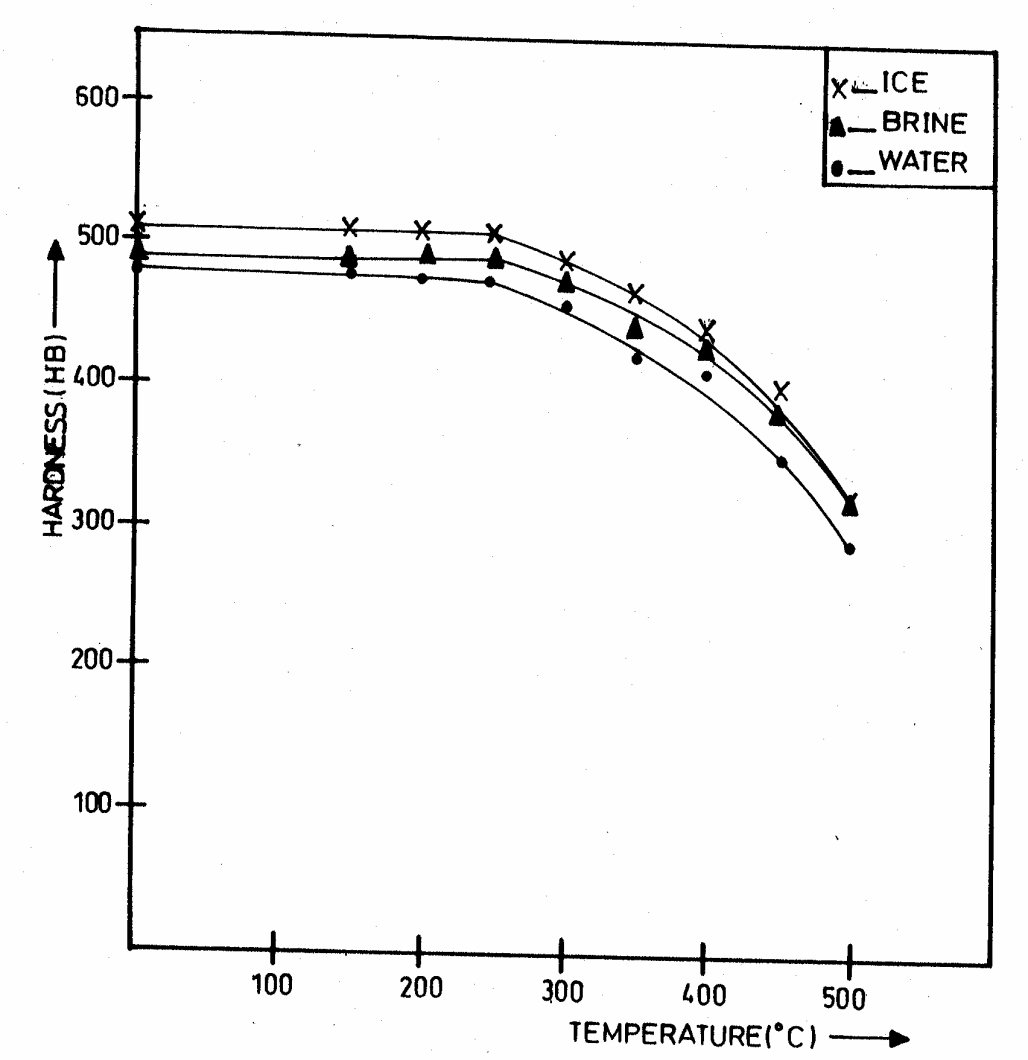


FIG. 4.3. EFFECT OF TREMPERING TEMP. ON HARDNESS (HB) OF SPECIMENS QUENCHED FROM 950oC IN WATER, BRINE AND ICE THEN TEMPERED FOR THIRTY MINUTES

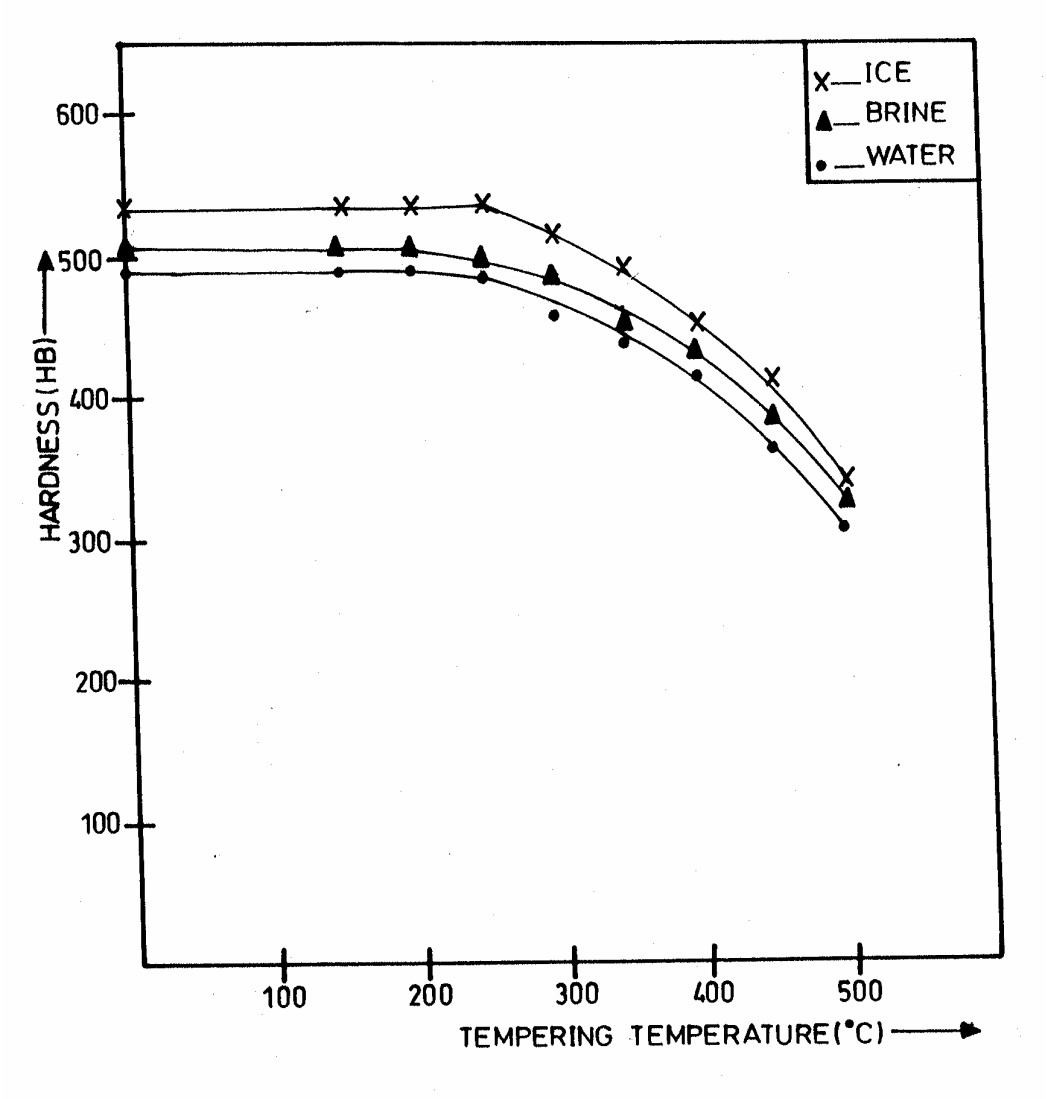
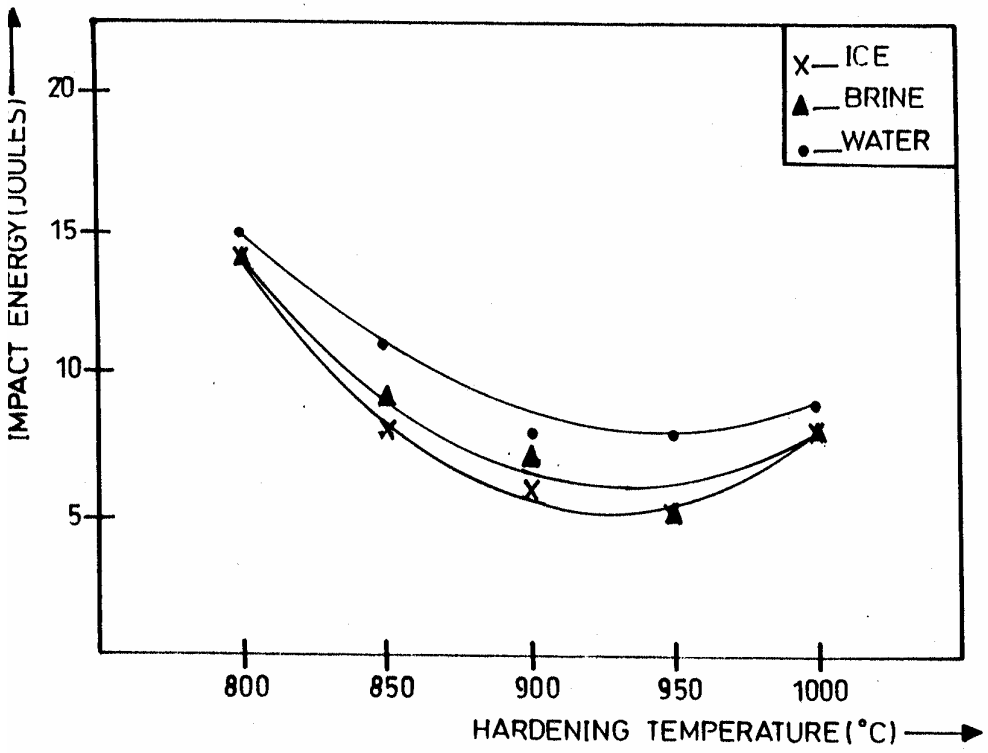


FIG. 4.4. EFFECT OF TREMPERING TEMP. ON HARDNESS (HB) OF SPECIMENS QUENCHED FROM 950oC IN WATER, BRINE AND ICE THEN TEMPERED FOR THIRTY MINUTES



5.4.5. EFFECT OF HARDENING TEMP. AND MEDIUM ON IMPACT ENERGY(J) OF SPECIMENS QUENCHED IN WATER, BRINE AND ICE.

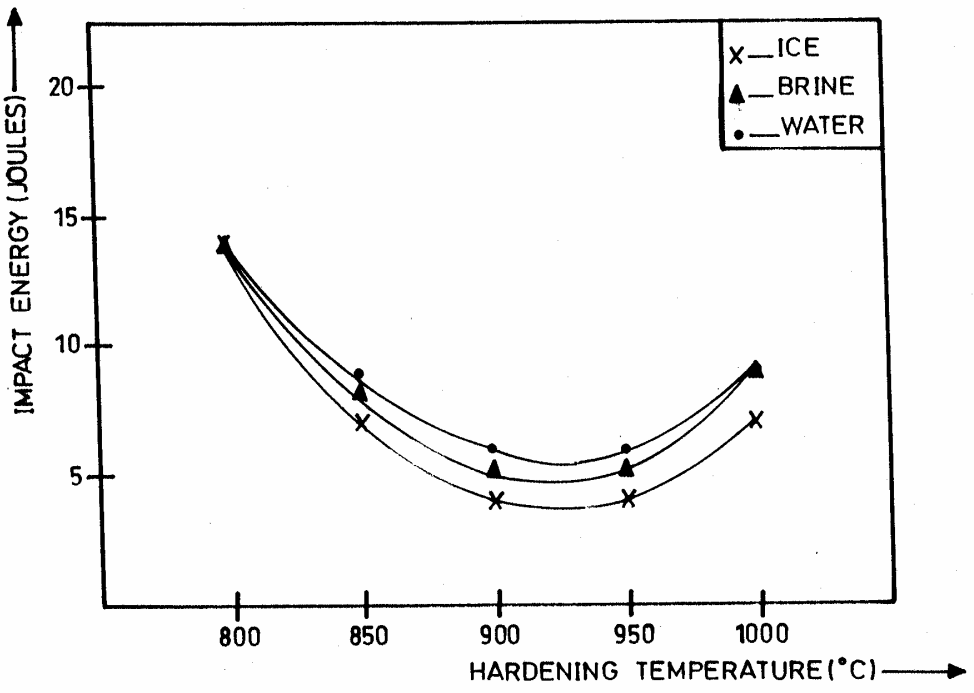
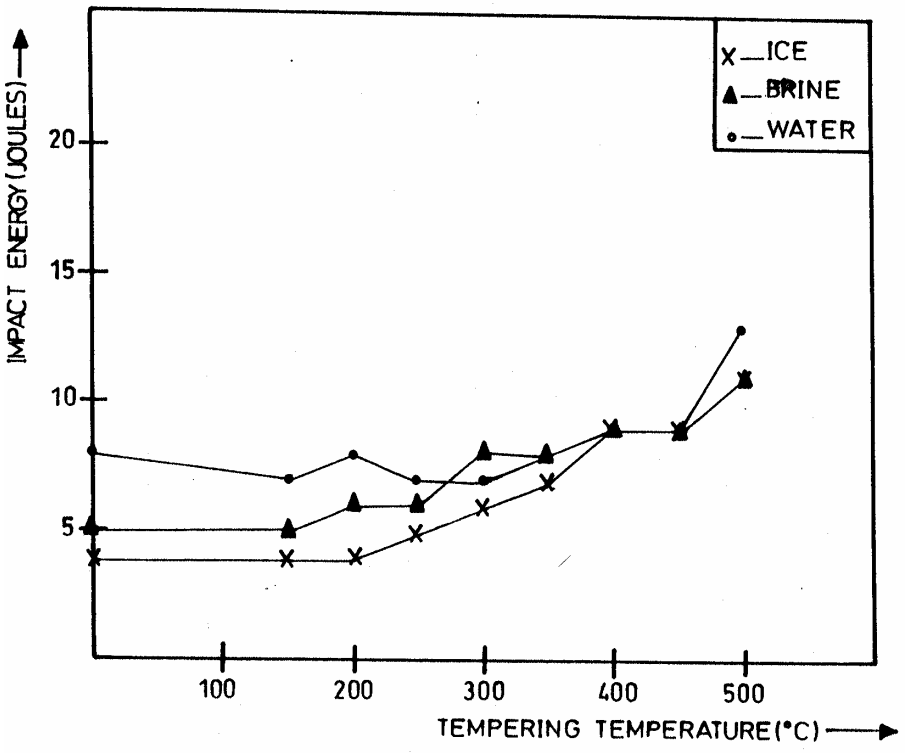
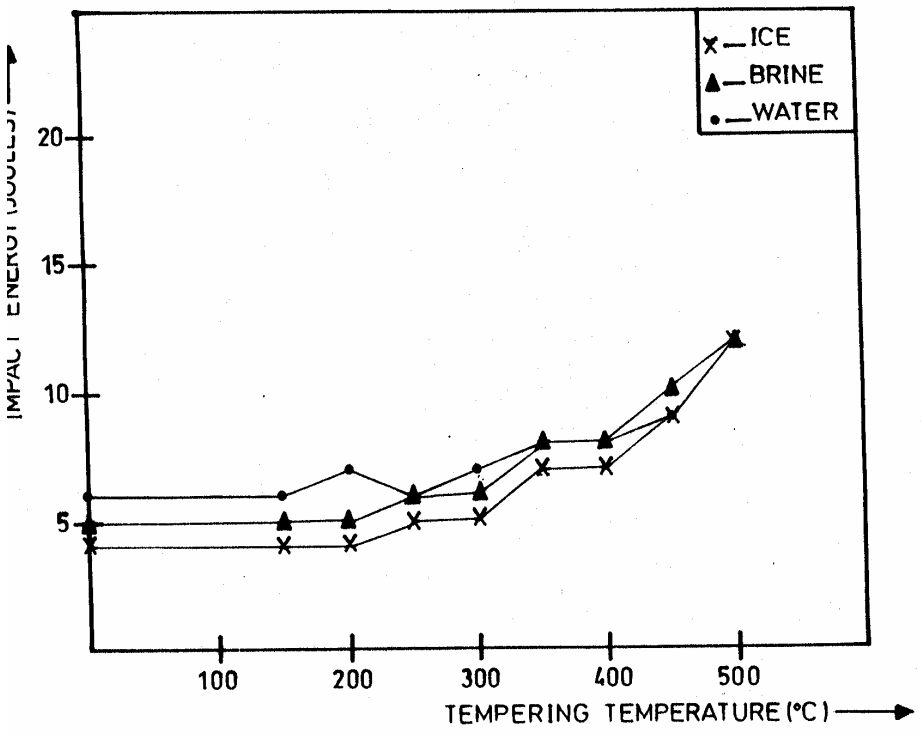


FIG. 4.6. EFFECT OF HARDENING TEMP. AND MEDIUM ON IMPACT ENERGY(J) OF SPECIMENS QUENCHED FROM 950°C IN WATER BRINE AND ICE THEN COLD TREATED.



3.4.7. EFFECT OF TEMPERING TEMP. ON IMPACT ENERGY(J) OF SPECIMENS QUENCHED FROM 950°C IN WATER, BRINE AND ICE, TEMPERED FOR THIRTY MINUTES.



5.4.8. EFFECT OF TEMPERING TEMP. ON IMPACT ENERGY(J) OF SPECIMENS QUENCHED FROM 950°C IN WATER, BRINE AND ICE, COLD TREATED THEN TEMPERED FOR THIRTY MINUTES.

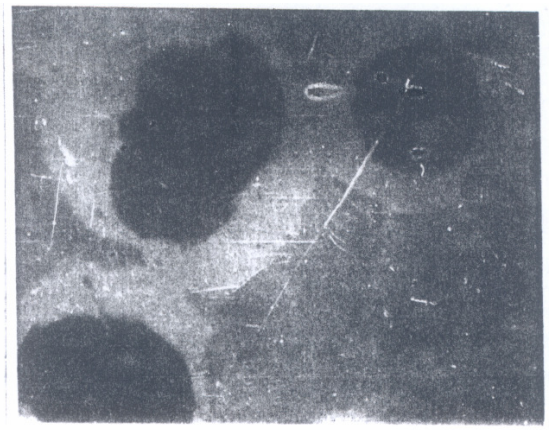


PLATE 4.1 X 300
AS CAST DUCTILE CAST IRON



PLATE 4.2; X 300
NORMALIZED DUCTILE CAST IRON

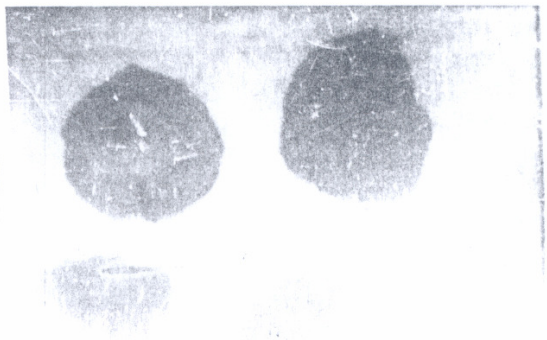


PLATE 4.3; X 300
DUCTILE CAST IRON QUENCHED FROM 800°c IN ICE WATE

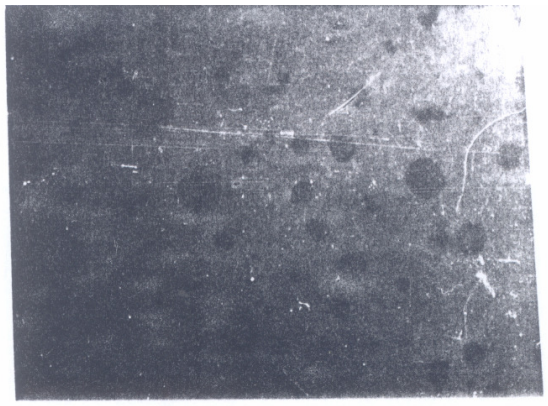


PLATE 4.5(a);
Cold treated Structure of Ductile Cast iron hardened from 950°C in water



PLATE 4.5(b);
Cold treated Structure of Ductile Cast iron hardened from 950°C in Brine



PLATE 4.5(c); X 100
Cold treated Structure of Ductile Cast iron hardened from 950°C in ice-water

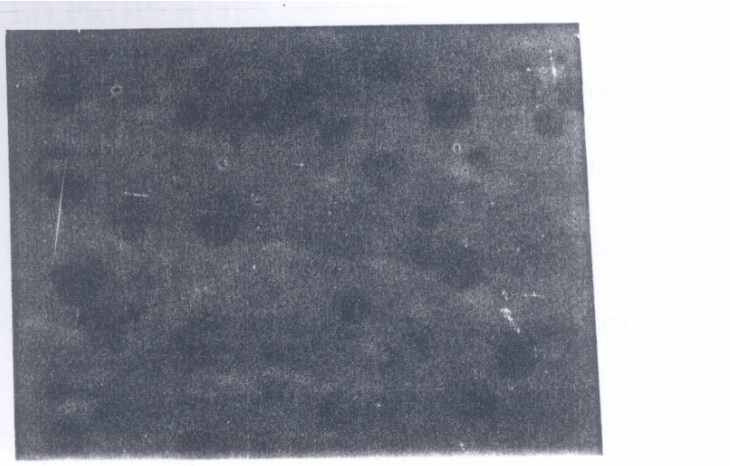


PLATE 4.5(d); X 100

ıctile Cast Iron Tempered for 30mins at 450°C

4.2.0 DISCUSSION

4.2.1 AS-RECEIVED PROPERTIES

The as-received hardness value of ductile cast iron was found to be 136HB, the impact strength was 22J as shown in fuhff4rkflr. The as-cast structure of the ductile cast iron was essentially ferritic with well distributed graphite nodules in a matrix of ferrite. There were h.owever, scattered pearlite colonies as shown in micrograph of plate 4.1

4.2.2 PRE-HARDNING TREATMENT

The micrograph in plate 4.2 shows the normalizing (pre-hardening treatment) structure of ductile cast iron. As expected, the normalized structure was completely pearlitic. The hardness and impact values are 168HB and 20 J respectively.

4.2..1 EFFECT OF HARDENING TEMPERA l'URE ON AS-QUENCHED PROPERTIES.

Appendix 2 and figure 4.1. show the as-quenched hardness values for ductile 1 cast iron specimens whicl~ were hardened by quenching in water; brine and ice water. Iti is observed that, the as-quenched hardness increased initially with the austenitizing 11 temperature and reached a maximum at about- 950°C. The same trend is observed for impact values as shown in figure 4.3: In this respect, the lowest impact values are for specimens quenched from 950°C. There is substantial increase in hardness when quenched between 800 and 900°C. The hardening range for this ductile cast iron is

found to be between 850 and 950°C where it attains maximum hardness. Quenching from 800°C resulted to incomplete austenitization; while full austenitization could he assumed to have taken place at about 950°C.

The increase betw~en 850 -950°C may be as a result of decrease in the percentage of retained austenite the structure, and not necessarily due to the increase in the percentage carbon content in the austenite matrix.

Significant increase in percentage carbon in austenite will be anticipated after full austenitization, and this will result in decrease in the as-quenched hardness as is in the case of austenitizing at 1000oC. Another reason for loss of hardness at these higher temperatures cOlild probahly he dlie to the effects of grain growth of prior alistenite grains due to high austenitizing temperature in addition to subsequent effect of retained austenite on quenching.

Hardening t-rom 800°C in the three media resulted to low and almost the same value (200HB) as shown in Appendix 2 and figure 4.1. this implies that 800"C is too Iowa temperatlire for forming full alistenite and having the austenite homogenous (Reynolds ~ ~ 1955). The presence of silicon (2.26%) in the ductile cast iron prohably could have contributed to the reduction (}f hardenability. This is becalise, according to Wilson (1975) silicon is one of the elements that stabilizes the ferrite phase, meaning that the presence of silicon will raise the temperature of austenite transformation hence higher temperatures will be reqliired to get the austenite completely transf()rmed to martensite;

4.2.4 RESPONSE TO SEVERITY OF QUENCH ~

As shown in figure 4.1, ductile cast iron showed good response to hardening in water, brine and ice water, which are higher than those reported by Dauda (1975) using the same hardening temperatures but quenching" in oil.

As expected, increase in the severity of quenching caused higher as-quenched hardness values. Oil quenching was found (Dauda, 1995), not to result in significant increase in hardness due to high percentage of retained austenite and low severity of quench, hence, may not be employed when high hardness values are essential, brine or ice-water quenching will serve better.

The hardness values of specimens quenched in ice-water was highest, those quenched in brine were .next. The probable reason could he due to the addition of highly ionized salt to water which decreased the viscosity of water and reduced the : duration of vapour blanket stage (Dell, 1978), then improving the cooling power of the aqueous solution (brine).

The least hardness values were obtained for specimens quenched in water from Ie; , all the austenitizing temperatures. This should be expected because ordinary water at room temperature as a quenchant will exhibit the three stages of heat removal (Rajan ~ ~, 1988).

It is significant to note that all the specimens were of standardized sectional size of 100 x 10m111 in order to facilitate comparative study in this respect.

4.2.5 POST QUENCHING COLD TREATMENT

Figure 4.2 and 4.6 show the results of hardness and impact tests conducted on ductile cast iron specimens that were c<;>ld treated for two weeks immediately after quenching from various austenitizing temperatures. In general, cold treatment resulted : in high hardness and lower impact values. Alsp"maximum hardness and lowest impact values were obtained for specimens austenitized at -980°C. The comparison of the hardness and impact values at this temperature in the two conditions is extracted and
t shown Appendix 6 and 7.

The effect of cold treatment increase with severity of quench of the media. This i is not as one would have expected considering that quenching in less severe medium ,"<'i{~j;: ~ would result in more austenite to be retained and which will be more readily availablef I for release. In addition, it is also known (Wilson, 1975) that less severity of quenching f promotes austenite stabilization.

4.2.6 TEMPERED PROPER'rIES

Figure 4.3 and 4.6 show the results of hardness tests obtained when ductile cast j~.,i_:: ~ iron specimens were quenched from 950°C in various media and tempered at various I~~~IJ~';;:~"'~ '" temperatures for thirty minutes. In all cases, softening commenced at about 300°C and c(;, reduced sharply thereafter. Hardness value of over 400HB was obtained in all cases for specimens tempered above 400°C. This is significantly higher than that obtained for plain high carbon steels which begin to soften rapidly at about 250°C (Dauda, 1995).

While prior cold treatment causes higher hardness values before tempering, it also causes these higher values to be retained for all tempering temperatures. However, ! r cold treatment of as-quenched ductile cast iron promotes the transformation of more hard phases.

Figures 4.7 and 4,.8 show the results of impact tests conducted on specimens that were tempered in as quenched and cold treated conditions. It is seen that the toughness of quenched and tempered ductile cast iron did not increase significantly until tempering I. was carried out above 400°C. However, it is significant to note that ductile cast iron ! does not suffer temper embrittlement as is the case with plain carbon steels (Gilbert, 1969).

CHAPl'ER FIVE

5.0 CONCLUSION AND RECOMMENDATIONS i

5.1 CONCLUSIONS

From this investigation, the following conclusions could be made:

I. Ductile cast iron responded very well to hardening in water, brine and ice-water, ice-water being the most significant.

2. While ice-water may have the above advantage, its use can only be limited to occasional use especially for very small samples/components.

3. Quenching of the ductile cast iron from 800°C did not result in any significant ; .. hardenability, hence, quenching temperatures less than 850°C should never be used.

4. Optimum hardening temperature was f()und to be between 900 alld 950°C. However 900°C is recommended fur hardening of the ductile cast iron. Because if 950°C is used cracking graphical

5. Cold treatment increased the hardness of all the specimens quenched. But more significant f()r specimens quenched in ice-water.

6. The t()llowing teillpering temperatures should be adopted:
   (i) 250 -300°C for wear resistance
   (ii) 350 -400°C for strength and toughness.

5.2RECOMMENDA TIONS ...

1. C:onvenient ways of quenching large components in ice-water should be sought.
2. Further work on austempering of Ductile cast iron using any economical method should he done. ,. I

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APPENDIX "-

Appendix 1. Hardness (HB) and impact (J) values of as-received and normalised specImens.

	Hardness (HB)	Impact (J)
AS- Received	136	22
AS- Normalised	168	20

Appendix 2: Hardness values (HB) of specimens quenched from various temperatures in different media and cold treated for two weeks.

Quenching Temperature(°C)	MEDIUM		
	Water	Brine	lce
800	198	200	205
850	315	365	410
900	430	466	485
950	480	490	511
1000	451	451	460

Appendix 3: Iwd impact (J) values for specimens quenched temperatures in different media.

Quenching Temperature(°C)	MEDIUM		
AS- Received	Water	Brine	lce
800	22	200	205
850	15	365	410 '
900	11	466	485 '
950	8	490	511
1000	8	451	460

Appendix 4: Hardness values (HB) of specimens quenched from various temperatures f in different media and cold treated for two weeks.

IQuenching Temperature .(OC	MEDIUM		
	water	Brine	Ice
800	200	205	205
850	325	370	415
900	445	476	496
950	490	503	535
1000	455	468	476

Appendix 5: Izod impact (1) values f()r specimens quenched temperatures in different media. And cold treated for two weeks.

Quenching Temperature (OC)	MEDIUM		
	water	Brine	Ice
800	14	14	14
850	9	8	7
900	6	5	4
950	6	5	4
1000	9	9	7

Appendix 6: Difference in as-quenched and cold treated values (HB) of speciemens quenched from 950°C in different media

	Hardness (HB)	Impact (1)
AS-Received	8	5
AS- Normalised	6	4
Difference	2	1

Appendix 8: Tempered properties (HB) of speciemen quenched from 950°C in various temperatures

Quenching Temperature (OC)	MEDIUM		
	Water	Brine	Lce
AS- Registered	480	490	511
150	478	490	511
200	478	490	511
250	478	491	511
300	460	476	492
350	428	447	470
400	416	430	446
450	352	384	400
500	297	322	322

Appendix 9: Tempered properties (J) of speciemen quenched from 950°C in various media and tempered at various temperatures. ':

Quenching Temperature (OC)	MEDIUM		
Water		Brine	Ice
AS Refri erator	490	503	535
150	490	503	535
200	490	503	535
250	486	503	535
300	461	500	535
350	442	845	517
400	418	431	492
450	363	308	411
500	306	3261	338

Appendix 10: Tempered properties (J) of speciemen quenched from 950°C in various :"i media and tempered at various temperatures.

Quenching Iem erature (OC)	MEDIUM		
	Water	Brine	Ice
AS Quenched	8	5	4
150	7	5	4
200	8	6	4

250	7	6	5
300	7	8	6
350	8	8	7
400	9	9	9
450	9	9	9
500	13	11	11

Appendix II: Tempered properties (J) of speciemens quenched from 950°C in 0- different media, cold treated for two weeks and tempered at various temperatures.

Quenching Temperature (OC)	MEDIUM		
	Water	Brine	Ice
AS Quenched	6	5	4
150	6	5	4
200	7	5	4
250	6	6	5
300	7	6	5
350	8	8	7
400	8	8	7
450	9	10	9
500	12	12	12