

**THE EFFECT OF VANADIUM AND MOLYBDENUM ADDITIONS  
ON THE MICROSTRUCTURE AND MECHANICAL PROPERTIES  
OF DUCTILE CAST IRON**

**BY**

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## DECLARATION

I declare that the work in this thesis entitled “The Effect of Vanadium and Molybdenum Additions on the Microstructure and Mechanical Properties of Ductile Cast Iron” has been performed by me in the Department of Metallurgical Engineering under the supervision of Engr. Dr. S. B. Hassan. 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 any university.

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## CERTIFICATION

This thesis entitled “The Effect of Vanadium and Molybdenum Additions on the Microstructure and Mechanical Properties of Ductile Cast Iron” by Muhammed Yakubu Ozovehe meets the regulations governing the award of the Degree of Masters of Ahmadu Bello University, Zaria, and is approved for its contribution to knowledge and literally presentations.

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## **DEDICATION**

I dedicate this work to Almighty Allah, the Lord of the Universe for His guidance and mercy before and during the period of the programme.

## ACKNOWLEDGEMENT

During the period of these programmes, I have profited immensely from working with many distinguished intellectuals in and outside the academia.

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## ABSTRACT

The effect of Vanadium and Molybdenum addition on the mechanical properties of ductile cast iron has been investigated. Alloys of ductile cast iron samples of varying additions of Vanadium and Molybdenum from 0.1-0.3% were produced into cylindrical test bars by sand casting process using “sandwiched” treatment method. Unalloyed ductile cast iron samples of the same base metal composition were also produced to serve as control and heat treatment samples. The heat treated samples were austenitized for the purpose of normalizing, hardening and tempering. Results of the mechanical properties revealed that tensile strength, yield strength and hardness increased from 456, 307N/mm<sup>2</sup> and 290BHN respectively for the unalloyed samples to maximum values of 560, 407N/mm<sup>2</sup> and 369BHN at 0.15% Vanadium addition and 562, 462N/mm<sup>2</sup> and 362BHN at 0.15% Molybdenum additions. Beyond 0.15% addition of both Vanadium and Molybdenum led to decrease in values of some of the properties. The impact values for the Molybdenum alloyed ductile iron increased with Molybdenum addition, while that of Vanadium got to a maximum at 0.2%V before decreasing. The heat-treated samples have higher tensile and hardness values, they are however, inferior to the Vanadium and Molybdenum alloys in terms of impact values. The yield strength of alloy grades are in some cases higher than the heat treated grades.

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## CHAPTER ONE

### 1.0 INTRODUCTION

Ductile cast Iron frequently referred to as nodular or spheroidal graphite iron is a recent member of the family of cast iron. It contains nodules of graphite embedded in a matrix of ferrite or pearlite or both, the graphite separates out as nodules from iron during solidification because of the additions of magnesium (Mg), cerium (Ce), or calcium, (Ca) introduced into the molten iron before casting (Kenawy and Fattal, 2001). Since the nodules act as crack arrestors, they improve the mechanical properties of ductile iron very significantly.

The formation of graphite nodules in ductile cast iron is practically not limited by the sectional thickness and mass of castings. High strength nodular cast iron whose structure is mostly pearlitic can be used as cast successfully and with economic benefits (Yanagisawa, 1995).

Ductile cast irons have found wide use in parts of engineering machinery, Agricultural equipment, Crankshaft of internal combustion engines, break drums, camshaft, clutch drums, cylinder bushing, connecting rods, caliper brake, gears, piston rings, plow shares, wheel hubs and pipe flanges (QIT Fer et Inc. 1983, Marston G. J. 1990).

Since 1948 when ductile iron became an industrial reality, the growth of ductile iron application has exceeded all expectations. Worldwide production was approximated to ten million tons and it is expected to reach 20 million tons by the turn of the last century and it has been projected that production will double by the middle of this century. The application of ductile cast iron is indeed a notable Engineering achievement of our age. It has exceptional properties, which combined the advantages of iron and steel (Decrop M, 1983).

The advantages of ductile iron that have led to its success are numerous but they can be summarized mainly as versatility and higher performance at lower cost. Other members of the ferrous casting family may have individual properties, which might make them the material of choice in some application, but none has the versatility of Ductile iron, which often provides the designer with the best combination of overall properties. The versatility is especially evident in the area of mechanical properties where ductile iron offers the designer the option of choosing high ductility with grades up or more than 18% elongation, or high strength with tensile strength exceeding  $825\text{N/mm}^2$  (Kersey, 1970). Austempered Ductile iron offers even greater mechanical properties and wears resistance providing tensile strength exceeding  $1.6 \times 10^3 \text{ N/mm}^2$  in some cases. (Kanawy and Fatai, 2001).

In addition to the cost advantages offered by all castings, Ductile cast iron when compared to steel and malleable iron castings also offers cost saving. Like most commercial cast metals usually decreased in volume during solidification and as a result required attached reservoir of liquid metal to offset the shrinkage, the formation of graphite nodules during solidification cause an internal expansion of ductile iron and as a result it may be cast free of significant shrinkage defects. This reduced requirement for feed metal, increase the productivity of ductile iron and reduced its materials and energy requirements resulting in substantial cost savings (Marston, 1990).

The automotive industries particularly the General motor corporation of United States and Toyota motor corporation of Japan (QIT Fer et Inc., 1983) expressed their confidence in ductile iron through the extensive use of this material in safety related components such as steering knuckles, brake calipers, camshaft, connecting rod, typhoid axle gears. Some of these components have been reportedly used as cast (Decrop, 1983).

One of the most critical material applications in the world is in containers for the storage and transport of nuclear wastes. The ductile iron nuclear waste container is another example of the ability of ductile iron to meet and surpass even the most critical quality test for material performance (Gilbert, 1968).

Except where high electrical conductivity, high ductility or good corrosion resistance are required, pure metals are rarely used for engineering applications. But such mechanical properties as tensile strength, hardness, impact, creep and fatigue can be improved by alloying.

Alloyed ductile cast iron are continuously been developed to provide special properties or meet the demands of service conditions that are too severe for conventional or Austempered ductile iron (ADI). Alloyed ductile iron depending on the grade can contain substantial levels of alloy in order to provide improved or special properties.

In the presence of alloy carbides, the abrasion and wear resistance of steels are improved. Some alloy carbides particularly Molybdenum carbide (MoC) and Vanadium carbide (VC) enhance the high temperature creep strength by providing a fine stable dispersion of particles in the matrix (Raghavan, 1983).

Because of the escalating energy cost, in addition to expensive heat treatment equipment, and the attendants risk of distortion and or cracking, during heat treatment of metals generally, this research therefore aims at studying the effect of addition of vanadium and molybdenum on the mechanical properties of ductile cast iron with a view to specifying them as-cast for engineering applications requiring high temperature properties.

## **1.1 Statement Of Problem**

- In most heat treatment processes, cracks, distortion and non-uniformity in hardness across the section are some of the problems encountered.
- This is in addition to the cost of heat treatment process that raise the overall production costs due to the high cost of heat treatment equipment and the very lengthy nature of the process with attendant high energy cost.
- Despite the recent researches on Austempered ductile cast iron for enhanced mechanical properties, the process is still entirely a heat treatment process that shared the already mentioned drawbacks.
- Similarly, the global energy crisis in generally and epileptic power supply in Nigeria can further increase processing costs and also hinder successful and satisfactory heat treatment operations.

## **1.2 Background Knowledge**

Despite the success recorded in the production and application of ductile cast iron over the years, the development has not been without difficulties. One of such difficult areas is in the addition of nodularizer to the base metal. Magnesium a widely used nodularizer has its boiling point lower than the melting temperature of iron thereby causing violent reaction

when contact with liquid iron resulting in low recovery of the metal (Metal Hand Book, 1979). This situation has caused increase in processing cost with the attendant's risk of poor mechanical properties.

Several methods have been developed to improve the recovery of magnesium. The recent process is the sandwiched treatment method with a reported recovery of over 80% (Foseco Handbook, 1994).

Another reason for this study is that heat treatment process is lengthy and energy cost can be expensive in addition to the costly heat treatment equipment. This study will therefore be very attractive particularly in Nigeria where energy supply has reached a crisis dimension.

### **1.3 Aims and Objectives**

The aims and objective include:

- i. To investigate the effect of vanadium and molybdenum addition on the microstructure and mechanical properties of ductile cast iron.
- ii. To create awareness and also encourage the use of alloyed ductile cast iron in the "as cast" condition for various engineering applications.
- iii. To reduce the overall total production cost of the ductile cast iron components.

#### **1.4 Significance of the Study**

This research finding will further enhance the economy of ductile cast iron production as the alloys can be used in the as-cast conditions. Furthermore, the resistance to softening and consequently mechanical properties deterioration can further be enhanced.

## CHAPTER TWO

### LITERATURE REVIEW

#### 2.1 INTRODUCTION

Despite the development of many sophisticated alloys in recent years, ferrous materials seem likely to remain the most important engineering alloys available (Higgin R. A., 1993 and Raghavan, 1989). Materials development during the ages generally refer to as stone, bronze or iron led to the production of more sophisticated equipment at this present age.

For over 90 chemical elements that exist, more than 70 of these are classified as metallic. Some twenty or more of the metallic lie in the groups of rare-earth and radio active metals which because they are very scarce and difficult to separate are chiefly of scientific interest only at the present time.

Although, a lot of progress was achieved during the first half of the last century in the development of grey and malleable irons, researchers have continued to search for the ideal cast iron an “as-cast iron” with mechanical properties equal or superior to malleable iron.

The common feature that all ductile irons share is the roughly spherical shape of the graphite nodules. These nodules act as crack arrester and make ductile iron very strong.

Vanadium addition to nodular cast iron along with molybdenum is a relatively new field but data on the effect of Vanadium and other Ferro-alloy in steel have been established (Foseco Foundryman, 1994 and

Higgins, 1993). Molybdenum and Vanadium are amongst the elements that form stable simple carbides, molybdenum carbide ( $M_6C$ ) and vanadium carbide ( $VC$ ), when added in small quantities. These carbides are in most cases harder than iron carbide ( $Fe_3C$ ). They are known to have effects on both the eutectoid temperature and composition resulting in delaying the austenite - pearlite transformation. As the temperature decreases, solubility of these elements decrease resulting in a strain induced precipitate of alloys carbides on a very fine scale.

The hot ductility of Nb-steel had been reportedly improved by the addition of 0.1% V to the steel (Raghavan, 1989). The addition of Vanadium and other strong carbide forming elements aimed at improving the strength of mild steel without impairing its excellent weldability had led to a new class of steel known as a micro alloyed steels (Raghavan, 1989 and Higgins, 1993). The total concentration of the micro alloying elements was less than 0.2%. Also 0.1 – 0.5% addition of vanadium have been reported to have refined the structure of the chill and minimizes coarse columnar grain structure (Sidney, 1974).

Research finding has revealed that addition of 0.5% Mo to steel decreased growth rate of pearlite by a factor of 100% (Raghavan, 1989). In other cases 0.3% Mo addition to Ni–Cr low alloys steel led to separation of pearlitic and the bainitic noses (Davis, 1983 and Raghavan, 1989).

Additions of up to 2% molybdenum to ductile iron containing 4-6% silicon were developed to enhance the high temperature strength of ductile iron capable of operating in applications such as exhaust manifolds or turbo charger casings. Molybdenum of about 0.1% has also been added to high silicon iron, which has been found to be very effective in increasing resistance to thermal fatigue (Cox, 1973).

The pearlite suppressing properties of molybdenum have been used to an advantage in irons of high chromium content (Metals Handbook,1978). The addition of 1 – 4% molybdenum is effective in suppressing pearlite formation even when the casting is slowly cooled in heavy sections. Molybdenum can replace some of the nickel in the nickel-chromium type of martensitic white iron. In heavy section casting in which 4.5% nickel would have been used, 1% molybdenum permits reduction of nickel content to about 3%. In light section castings where 3% nickel would normally be used, additions of 1% molybdenum permits reduction of nickel to 1.5%.

Molybdenum in quantities of about 1-4% has been used effectively in enhancing corrosion resistance especially in the presence of chlorides. In quantity of 1% or less it improves high temperature strength, creep resistance and resistance to softening (Metals Handbook,1978). Ductile iron is indeed a material that offers a wide range of properties through microstructural control. Based on the matrix developed, ductile iron can be grouped as:

Ferritic ductile cast iron: This is a ductile cast iron having its graphite nodules in a matrix of ferrite which is basically pure iron conferring the grade with high impact resistance and good machinability.

Pearlitic ductile cast iron: This is a ductile cast iron whose nodules can be embedded either in a mix matrix of ferrite and pearlite or in a fully pearlitic matrix. This grade has moderate ductility high strength, good wear resistance and good machinability.

Martensitic ductile cast iron: This is a ductile cast iron, which in the as-cast condition is hard brittle and are seldom, used. However tempered martensite has very high strength and wear resistance.

Banitic ductile cast iron: This is a ductile cast iron that can be obtained as cast in 50mm or thicker section sizes by alloying or by an isothermal heat treatment after quenching in all section sizes. Very high strength and adequate elongation can be obtained in all section thickness.

Austenitic ductile cast iron: This is a ductile cast iron that is never chosen for strength alone. The outstanding features are good corrosion and oxidation resistance and dimensional stability at elevated temperature.

The importance of matrix in controlling properties is emphasized by the use of matrix names to designate the various types of ductile iron

(Deccrop M., 1983). Martensitic, bainitic and austenitic grades can be obtained through alloying and/or by heat treatment.

## **2.2 Principle Of Alloying**

According to the Hume Rothery's rules, (Raghavan, 1989) the conditions that favour extensive substitution solid solutions are: Size difference, Electro negativity, Crystal structure.

Molybdenum and vanadium form solid solution with iron but tend to stabilize the ferrite phase in preference to austenite since they have the same crystal structure as ferrite.

They reduced the extent of the austenitic area on the equilibrium diagram by forming a gamma loop. The austenite region is enclosed within the loop. At a particular level the  $\alpha$  -ferrite and  $\delta$  - ferrite region merged and become continuous. The critical composition at which austenite phase disappears is 3% and 2% for molybdenum and vanadium respectively.

Fig. 1: The Fe-Cr equilibrium diagram illustrates the formation of a gamma loop (Raghavan, 1989).

Since carbon is an austenite stabilizer, a higher concentration of a ferrite-stabilizing element is required to eliminate the austenite field from the phase diagram (Raghavan, 1989). A value of 6.4 and 4% molybdenum and vanadium respectively have been reported. Since austenite cannot be produced in such composition, such alloys are classed non-heat treatable.

### **2.3 FERROUS MATERIALS**

Before the advent of ductile iron in 1948, various grades and classes of iron and steel were used for different engineering applications. Iron and carbon exhibit complete liquid solubility but only partial solid solubility. Since pure iron is allotropic. It can exist in more than one physical form. It has a body centred cubic, which is stable up to 910°C when it changes to a faced centered cubic structure (Davies, 1983). A further change takes place at 1390°C when the FCC iron reverts back to BCC form. Since the atoms in the FCC lattice are more densely packed together than in the BCC, the change from FCC to BCC on cooling is always accompanied by contraction.

The addition of carbon to iron lowers the freezing points of the metal and also alters the temperatures at which the changes in crystal structure

occur. Body centered cubic iron has only very slight solid solubility for carbon to form a solid solution Ferrite at low temperature and  $\delta$  - Ferrite at high temperatures. Face centered cubic iron can dissolve up to 2.11% carbon to form a solid solution called Austenite. Ferrite contains a maximum of 0.01% carbon and is soft, ductile and readily cold-worked. Austenite is nearly non- magnetic and is also soft and ductile. Carbon also reacts with iron to form a hard, brittle compound  $\text{Fe}_3\text{C}$ , which is called Cementite. The decomposition of Austenite at  $723^\circ\text{C}$ , which is generally refer to as eutectoid reaction yields Pearlite, an intimate mixture of lamellar cementite in a matrix of ferrite.

Martensite is a supersaturated solid solution of carbon in iron produced by rapid cooling. It is normally heat-treated to reduce the carbon content by the precipitation of carbides to provide a controlled combination of high strength and wear resistance.

Bainite is a mixture of ferrite and carbide in a non-lamellar form produced by alloying or heat treatment.

## **2.4 Cast Irons**

The term Cast Iron identifies a large family of ferrous alloys. Cast Irons primarily are alloys of Iron, Carbon and Silicon in which more Carbon is present than can be retained in solid solution in Austerite at the eutectic temperature.

Wide variations in properties can be achieved by varying the balance between Carbon and Silicon, by alloying with various metallic or non-metallic elements, and by varying melting, casting and heat treating practices.

As the name implies, Cast Irons are intended to be cast to shape rather than formed in the solid state. Cast Irons have low melting temperature, are very fluid when molten, do not form undesirable surface films when poured, and undergo slight to moderate shrinking during solidification and cooling. However, Cast Irons have relatively low impact resistance and ductility which may limit their use (Sidney, 1974).

Mechanical properties of Cast Iron especially strength, ductility and modulus of elasticity depend strongly on structure and distribution of microstructural constituents. Physical properties such as thermal conductivity and damping capacity also are strongly influenced by microstructure. In any Cast Iron, the microstructural features that have the most significant effect is free graphite. Shape and distribution of free graphite are more useful than composition ranges for different types of cast iron overlap and in many instances iron of a given composition can be made into any of the four basic types by varying casting or heating practices. The structure of the matrix surrounding the free graphite particles also influences mechanical properties (Sidney, 1974).

The four basic types of cast iron are White Iron, Grey Iron, Malleable Iron and Ductile Iron. Beside the four basic types there are other specific forms of Cast Iron to which special names have been applied.

Chilled Iron, is White Iron that has been produced by cooling very rapidly through the solidification temperature range. An area of the casting that solidifies at a rate intermediate between those of Chilled Iron and Grey Iron, and which exhibits microstructural and fracture-surface features of both type is known as Mottled Iron. Compacted graphite Cast Iron also known as Vernicular Iron has a structure intermediate those of Grey Iron and Ductile Iron.

#### The Iron-Iron Carbide-Silicon System

A section through the ternary Fe-Fe<sub>3</sub>C-Si diagram at 2% which approximates the Silicon content of many Cast Irons provides a convenient reference for discussing the metallurgy of Cast Iron. The Fe-Fe<sub>3</sub>C-Si system; the eutectic and eutectoid points shift to lower Carbon content. The Figure represents the metastable equilibrium between Iron and Iron Carbide (Cementite), a metastable system. The Silicon that is present remains in solid solution in the iron, in both ferrite and austenite and so does not affect the composition of the Carbide phase but only the conditions and the kinetic of Carbon formation on cooling. The designation  $\alpha$ ,  $\gamma$ , and Fe<sub>3</sub>C therefore

are used in the ternary system to identify the same phases that occur in the Fe-Fe<sub>3</sub>C binary system.

It is generally accepted that the composition of these materials be described in terms of both the composition of carbon, silicon and phosphorus. Thus the term carbon equivalent CE has been adopted where

$$C. E. = \%C + 1/3\% Si + \%P \text{ (Davies and Oilman, 1983)} \text{-----} \text{--(1)}$$

Hence C. E Carbon Equivalent is an index to convert the amount of these elements into equivalent amount of carbon.

In the iron-carbon system, eutectic occurs at 4.3% carbon. Therefore a carbon content greater than 4.3% would be expected to give a hypereutectic structure, whereas a carbon content less than 4.3% should give a hypo-eutectic structure.

Fig 2: Iron-Iron Carbide-Silicon Ternary Equilibrium System (Metals Handbook, 1978)

#### **2.4.1 Grey Cast Iron**

This is a form of cast iron in which the carbon precipitates as flake graphite. The fractured surface has a dull grey appearance due to the presence of about 12% by volume of graphite (Foseco Foundryman 1994).

The great merits of grey iron as a casting alloy which still remain true today are its low cost, its high fluidity at modest temperature and the fact that it freezes with little volume change since the expansion of the carbon precipitating as graphite compensates for the shrinkage of the liquid iron. This means that complex shapes can be cast without shrinkage defects. These factors together with its free-machining properties account for the continuing popularity of gray cast iron, which dominates world tonnages of casting production (Angus, 1978).

#### **2.4.2 Classes of Grey Cast Iron**

Grey irons are often specified by their minimum tensile strength. In most instances, the chemical composition is not specified; rather it is the

tensile strength and Brinell hardness which are written into specification for certain applications.

The British standard specification for grey cast iron is BS1452 in which seven grades of materials are specified with minimum tensile strength of 155, 185, 205, 260, 310, 355 and 400N/mm<sup>2</sup> respectively (Davies, 1983).

Based on these specifications gray cast irons are being classified as.

(i) Low Strength High Fluidity Irons.

The high fluidity is achieved by using high phosphorus content up to about 1.5% together with a high silicon content of 2.5 to 3.0%. The mechanical properties of iron are not of great importance. The usage of this type of cast iron has dwindled considerably, although it is still used for such articles as manhole covers.

(ii) Engineering Iron:

This class have reasonable strength with good castability. The type of matrix structure produced is controlled mainly by adjustment of the carbon and silicon content in relation to the thickness of the casting. The silicon content may be up to 2.5% for thin sectioned castings, but as low as 1.2% for thick sectioned. The sulphur and phosphorus contents are kept low because they tend to cause brittleness. But phosphorus cannot be decreased below about 0.3% because of the need for reasonable fluidity. The graphite flakes, though Detrimental

to the mechanical properties ensure good machinability because they act as chip breakers and their large bulk helps to improve castability by counteracting solidification shrinkage. This class is usually produced out of grade 12 and 14 having 185 and 215 N/mm<sup>2</sup> minimums tensile strength respectively (Sidney, 1974).

(iii) Heavy Duty Irons:

For the higher tensile grades i.e. grade 17 and above, whom this grade represents, the iron will require inoculation before casting or the addition of alloying element.

Inoculation may be carried out by adding a graphitizing agent such as ferrosilicon or calcium silicide to the molten iron contained in a ladle. The effects of inoculation include inhibition of under cooling and consequent chilling or weak structure and also provide better grain structure.

### **2.4.3 Microstructure of Grey Cast Iron**

Matrix microstructure of grey cast iron depend in a complex way upon the graphite size and shape, the carbon equivalent, the section size the processing history and the alloyed content (ASTM standards, 1987). Most grey cast irons are hypoeutectic in composition. In the hypoeutectic grey

cast irons, the proeutectic austenite dendrites are the first constituent to form.

From the stable and metastable iron systems, the austenite matrix microstructure exist over a range of temperature from the eutectic temperature down until the temperature range where the austenite will begin to transform to either the stable ferrite plus graphite or the metastable ferrite plus cementite (pearlite). According to the phase diagram the cooling alloyed first encounters the stable phase field in which ferrite can first appear. It is possible for the ferrite to nucleate on graphite a convenient place to deposit the carbon from the austenite that cannot be absorbed by the bcc ferrite which has only a solubility of about 0.01% C.

If the casting cools slowly enough the ferrite nuclei can continue to grow into the austenite, the excess carbon diffusing through the ferrite into the waiting arms of graphite flakes. Were these to occur to completion, the final structure would be ferrite and graphite. This is the equilibrium microstructure predicted by stable phase diagram (Mikhailov, 1989). If the casting on the other hand was cooling quite rapidly or if there were significant amount of alloy, the austenite may find it easier to transform the remainder of the austenite to pearlite (ferrite + Fe<sub>3</sub>C). The cooling rate is however a function of the section thickness.

Fig. 3: The microstructure of gray cast iron consists of graphite flakes in a matrix of ferrite.

## **Morphology of Graphite**

Large graphite flakes seriously interrupt the continuity of the pearlitic matrix thereby reducing the strength and ductility of the grey iron (Sidney, 1974). Small graphite flakes are less damaging and are therefore generally preferred. The standard method of defining forms is based on the system proposed by the American Society for Testing and Materials, ASTM specification A247 (Foseco Handbook, 1994) which classifies the form, distribution and size of the graphite. Certain requirements must be met before a sample is evaluated. Attention must be paid to the location of micro-specimen in relation to the rest of the casting, the wall thickness and the distance from the as-cast surface. Care is also needed in grinding and polishing so that as much graphite as possible is retained in a representative cross-section. The specimen is normally examined in the polished unetched condition of a magnification of X100 and with a field of view of about 80mm (Foseco Handbook, 1994).

Slow cooling of hypoeutectic iron to favour graphitization also produces large crystals of primary austenite. This can restrict the eutectic mixture or graphite to the grain boundaries and results in graphite flakes that are relatively few in number and coarse.

Increasing the carbon to increase the amount of the eutectic also increase the amount of graphite formed. This may weaken the cast iron more than a smaller grain flake size can strengthen it. Increasing the silicon

content increases the amount of eutectic formed thus reducing flake size. However, since high silicon content has such a high graphitizing influence, the matrix will probably be ferritic resulting in a weak casting (Sidney, 1974).

The five flake types are shown below:-

Fig 4: Graphite Flakes Types (Metals Handbook, 1978)

Type A results from uniform distribution of flakes of uniform size and is the preferred type for engineering application. This type of graphite structure forms when high degree of nucleation exist in the liquid iron,

promoting solidification close to the equilibrium graphite eutectic (Foseco Handbook, 1994).

Type B is the rosette pattern of graphite flakes. It is common only in the intermediate region of a chilled cast iron. This region is known as the mottled region and consists of a mixture of grey and white cast iron.

The few large, straight graphite flakes present in type C always indicate that the iron is hypereutectic in carbon content. Silicon and several other alloying elements reduce the carbon content of the eutectic and if they are present in sufficient amount the eutectic composition may be reduced to below 3.5% carbon.

Type D and type E flake patterns usually result from the graphitization of normal eutectic structure. These types appear in irons of very high purity or in commercial irons that have been cooled rather rapidly during solidification. Although the graphite flake size is small, the interdendritic pattern and high graphite content weaken the material. Therefore, type D and E flake pattern are undesirable in gray iron (Sidney 1974).

#### **2.4.4 Application of Grey Cast Iron**

The Application of grey cast irons are many and varied including the following (Davies, 1983).

- i. General Engineering: - Lathe, and machine casting
- ii. Automobile Engineering: - Cylinder Block, brake drum and disc
- iii. Marine Engineering: - Pump casing
- iv. Metal production: Ingot moulds, rolls

#### **2.4.5 White Cast Iron**

When the graphite in iron exists in a combined state called cementite (both the free  $\text{Fe}_3\text{C}$  and the eutectoid  $\text{Fe}_3\text{C}$ ) the resultant effect is an iron very hard and unmachinable usually referred as white cast iron. It is usually used in as-cast condition after final grinding.

A typical composition range would contain 2.5 to 3% carbon with 0.75 to 1.5% silicon (Foseco Handbook 1994). They are used in application requiring an inexpensive material with high surface hardness e.g. for earth moving machineries, crushing and grinding equipment.

White cast iron can be hypoeutectic or hypereutectic depending on the composition. A hypoeutectic irons will solidify initially by the formation of austenite dendrite and the interdendritic areas eventually solidify as a eutectic of cementite and austenite (called Ledeburite). Further cooling will cause the austenite to transform to pearlite, an alternate lamellae of ferrite and cementite. The structure at room temperature is

therefore one of primary dendrites of pearlite with interdendritic areas of transformed Ledeburite.

Hyper- eutectic irons will solidify initially by the formation of needle of primary cementite so that at room temperature the structure will consist of massive primary cementite in a matrix of transformed ledeburite.

Fig. 5: The Microstructure of white cast iron.

#### **2.4.6 Malleable Cast Iron**

Malleable cast iron has been produced by human beings for thousands of years but it is slowly but surely being replaced by ductile cast iron, due to cost of production and limitation on section size that can be produced in the malleable state. (Davies, 1983) This is a material with lower carbon (2.0-2.6%) and lower silicon (1.1-1.6%) unlike grey cast iron, which promotes the formation of white hypoeutectic cast iron before a prolonged annealing heat treatment is applied. The hypoeutectic first solidify by forming austenite dendrites and then the eutectic austenite + cementite ( $\text{Fe}_3\text{C}$ ).

A comparison of the United States production of malleable, ductile and grey cast irons illustrates that malleable cast iron production has declined and most of the formal applications have been replaced by ductile cast iron (Foseco Handbook, 1994).

The aims of the annealing treatment is to improve the ductility of the cast iron by causing the cementite (both the free  $\text{Fe}_3\text{C}$  and the eutectoid  $\text{Fe}_3\text{C}$ ) to break down into ferrite and rosettes of temper carbon. The more rounded form of the rosette avoids the stress – concentrating effects of flake graphite and also a softer matrix is produced with either or no pearlite. The ductility of the iron as measured by the % elongation of a tensile test piece is increased from almost zero to between 5 and 15% as a result of the annealing (Davies, 1983).

Two types of malleable cast iron have been in used. These are the white heart and Black heart. The British standard specification for white heart iron is BS 309 (Grades 1 and 2) and the Black Heart iron is BS 310 (Grades 1, 2 & 3) (Foseco Handbook, 1994, Davies, 1989).

#### **2.4.7 Ductile Cast Iron**

Ductile iron also known as spheroidal graphite iron or nodular iron, is made by treating liquid iron of suitable composition with magnesium before casting. This promotes the precipitation of graphite in the form of discrete nodules instead of interconnected flakes. The nodular iron so formed has high ductility, allowing castings to be used in critical application such as automotive transmission components, agricultural implement parts and water pipes (Foseco Handbook, 1994).

Fig 6: Spheroidal nodules of graphite in SG iron.

(Foundry Metallography, 1980)

#### **2.4.8 Production of Ductile Cast Iron**

Universally the production of ductile iron almost utilizes a process by which the molten iron is “treated” with magnesium just prior to castings, followed by inoculation with a ferrosilicon alloy in much the same way as for the production of grey cast iron. In this process the magnesium whose boiling point is at a lower temperature than the melting point of cast iron is usually added to the melt in the form of a master alloy which contain 5% magnesium (Mikhailov, 1989 and Decrop, 1983). This alloy is aimed at reducing the violence of the reaction that occurs when the molten iron contacts the magnesium.

The presence of magnesium in the liquid metal fades off due to the high vapour pressure of the magnesium requiring that the cast must be poured within a short time after treatment usually less than 5 minutes.

It is necessary that Sulphur content be kept below 0.01% for successful treatment because of the ability of the Sulphur to react with the Mg forming ( $Mg_2S$ ) and remove elemental Mg from the melt. Often times the melt needs to be desulphurized before treatment can progress except where high purity charge materials are available.

Desulphurization process usually involves addition of calcium to combine with the Sulphur to form calcium sulphide which rise to the slag layer and can be skimmed (Decrop, 1983).

The use of shaking ladle with an eccentric rotating movement, which creates a wave of metal, which as it breaks, covers the reactive alloys, has also been practiced. A similar result can be obtained by setting in motion only the contents of the ladle, not the vessel. This being done with much less expensive equipment, the OSTBERG tubular refractory agitator which develops a movement from top to bottom of the bath (Decrop, 1983). This process has been intended more particularly for treatment of large quantities of iron, which allows the operation of desulphurization and magnesium addition to be carried out in succession. Another method known as MEEHANITE FLOTRET treats the metal with a low Sulphur content as it flows through a reaction chamber placed above the casting ladle. This is sometimes referred to as “inmold” process applied to the ladle. It has the advantages of eliminating fumes while also ensuring a very high magnesium yield.

Micro-structures of magnesium treated and properly inoculated irons with carbon equivalent greater than 4.3 are made of graphite nodules surrounded by ferrite (QIT Fer, 1983). The final as-cast microstructure depends upon the combination of section size, alloy content and processing

history. Typical as-cast microstructure consists of a bull eye structure of ferrite surrounding graphite nodules which in turn is surrounded by pearlite.

#### **2.4.9 Properties of Ductile Cast Iron**

The mechanical properties of ordinary iron are limited by the presence of the graphite flakes, which act as notches in the matrix. The spheroidal form of the graphite is an effective remedy for this inferiority and the strength of ductile cast iron is thus close to that of steel (Higgins, 1993 and Marston, 1990).

With good spheroidal graphite, the strength and elongation properties are close to that of steel, while an imperfect form of graphite comprising flakes and quasi-flakes (spheroids which have degenerated into short thick lamellae) will give results which are intermediate with those from ordinary iron, and in particular low elongation values. The structure obtained thus plays a critical part on the mechanical properties, The properties may vary between tensile strength  $392 - 539 \text{ N/mm}^2$ , elongation 24 – 15% for a ferrite structure and tensile strength  $588 - 883 \text{ N/mm}$  with elongation, 8 to 3% for pearlite structure (Motz and Orths, 1967).

Although Carbon reduces properties, the effect is however much less marked than for the flake graphite iron which is (about 4 times less). Silicon and manganese increase strength and reduce elongation. There is a risk however that this element may lead to carbides, a draw back that can be

avoided with nickel which also make it possible to obtain very high properties (Maccaulay, 1971).

Although phosphorous slightly increases the strength of ferritic iron, it reduces that of pearlitic iron and elongation in both cases. In practice the content of this element in ductile iron is always kept at 0.10 maximum.

Ductile cast iron like steel under tension obeys the law of proportionality of stress and elongation within the range of elastic deformation. The modulus of elasticity is thus clearly defined which is generally between 17,000 to 18,000 kg/mm<sup>2</sup>.

The impact strength of ductile iron can be compared with those of steel which are appreciably higher. The strength of both ferritic and pearlitic ductile cast iron diminishes appreciably in hot conditions when the temperature exceeds 300°C. On the other hand elongation increases markedly beyond 500°C. The yield stress varies like tensile strength.

Annealed ferritic iron at 20<sup>0</sup>C has a tensile strength of 41kg/mm<sup>2</sup> with 2.7% elongation. At a temperature of – 269<sup>0</sup>C this same grade of iron has its tensile strength equal to 66.5kg/mm<sup>2</sup> with 1.4% elongation (Motz and Oxth, 1967).

Vibration damping capacity of ductile cast iron, a property very important for structural components such as machine frames where the effects of resonance from undamped vibration may be particularly detrimental is at least higher than steel and next to flake graphite iron.

Where a factor of 100 is taken for steel, ductile cast iron would be 2.5 times and flake graphite 4 times the value of steel (Cox, 1973).

Ductile cast iron has a distinct advantage over steel, castability and machinability. This superiority is obvious in the case of castability. The normal casting temperature of ductile cast iron is  $1400^{\circ}\text{C}$  much less severe on moulds than the temperature of steel, making it possible to ensure improved soundness in castings and a better surface appearance. With respect to machinability ductile cast iron is much superior to that of steel of the same tensile strength.

The idea that softness makes for easy machining and hardness for difficult machining is only partly true (Kent, 1990). Pure ferrite or structure with much ferrite uninterrupted by harder constituents are gummy, and stick to the tool producing a rough finish. Ductile iron will thus withstand higher cutting speeds than grey iron of the same hardness.

## **2.5 Melting Furnaces**

The necessity of having liquid iron with a low sulphur content in order to produce ductile cast iron has been suggested (M. Decrop, 1983). The presence of sulphur not only brings the disadvantage of increasing magnesium consumption but also leads to formation of magnesium sulphide with the risk that this may be localized in casting in the form of inclusions, with an adverse effect on soundness and mechanical properties. This is

therefore, a fundamental point in selecting the melting furnaces for ductile iron production. Today, ductile cast iron is being produced satisfactorily from many different types of melting furnaces such as:

1. Electric Furnaces
2. Cupola Furnaces
3. Rotary Furnaces
4. Crucible Furnaces

## ELECTRIC FURNACE

With Electrical Melting, it is possible to obtain a liquid iron which attain the sulphur content introduced in the charge together with the special advantages of flexibility (temperature analysis and metal-flow rate control) while also being very convenient to operate. Electric Furnaces include Resistance Furnaces, Arc and Induction.

### **Resistance Furnace.**

This type of plant which is not very widely used has a capacity of 50kg – 1 ton and furnaces power varies accordingly (with increasing capacity) between 1kw and 1/2kw/kg of capacity. A low voltage is used (20 to 50) but high current density (4 to 5,000A) which can be regulated so as to adjust heat output, which is very precisely and flexibly controlled, in order to suit the required working conditions.

The principle of indirect heating used in this type of plant involves high energy consumption possibly in excess of 900kWh per tonne. Rod wear, which leads to variations in resistance during use, is a slight complication in furnace control and appreciably increases operating costs. Especially as it is not possible to retain the rod until it is completely worn (as an example of consumption, one rod per four melts of iron) and the rod may also break, leading to accidental carburisation of the bath.

### **Arc Furnaces**

The direct-arc Heroult-type furnace is used for the production of spheroidal graphite base irons and provides a very flexible melting unit enabling spheroidal graphite iron to be produced from a wide range of raw materials (Hassan, 2002). However, direct-arc furnaces are more generally used for steel production.

### **CUPOLA FURNACE**

An ordinary cupola with a rammed silica lining uses coke with good thermal efficiency, at present of the order of 30% and above. It operates continuously and the iron flowing over the surface of the coke charge undergoes the chemical reactions of carburization and sulphurisation during melting. The acid cupola thus gives iron with a fairly high sulphur content, all the more so since the coke rate and proportion of returns (or iron scrap)

are higher; normally 0.08 to 0.12 but possibly 0.15 or above. With a burden containing new iron (50% for example) the sulphur content in the liquid iron may drop to 0.06, which is still too high for SG iron. A prior desulphurization treatment, accompanied by deslagging and possibly re-lading, appreciably cool the iron (60 to 80°C for desulphurisation; 30 to 50°C for re-lading) (M. Decrop, 1983). It is difficult therefore, to use a cold blast acid cupola for SG iron and it is often necessary, in these circumstances, to supplement the melting plant with a duplexing electric furnace for mixing and reheating the liquid iron.

The limits to the use of an ordinary acid cupola are therefore, basically determined by the final temperature of the iron. A basic cupola can supply iron with a lower sulphur content, which becomes lower as the slag basicity index rises; normally it is essential to obtain S equal to 0.03% without difficulty but this basic slag, with a very high melting temperature, involves control difficulties in an ordinary cupola and, under practical conditions, requires blast preheating in order to obtain regular working without hanging of the charge. The conventional cupola cannot provide a satisfactory solution to this problem and it is necessary to consider a more complex and expensive plant with an air preheater. This type of plant can only be economic for fairly substantial output with a minimum production of the order of 30t/day. In practice these plants operate without a lining in

the shaft, which is water cooled, and with a neutral lining in the hearth (a carbon ramming mix).

## INDUCTION FURNACE

The best solution for melting SG irons is the Induction Furnace. This furnace is basically of two types;- the Channel and the Coreless

### **The Channel Furnace**

The Channel Furnace is basically an upper vessel holding the bulk of the charge material, with an inductor bolted on the underside (Foseco Handbook, 1994). All the power is induced within the inductor heating a loop of molten metal, which transfers its heat to the main body of the charge by convection and induction forces. Channel Induction Furnaces are rarely used because of the difficulties in preserving the refractory and the temperature reached in the spout but some low-power furnaces of this type are reportedly in use (100 to 1000 kW for capacities of 800kg to 20t), either in order to hold at temperature (operating in duplex with a cupola) or for continuous melting. The temperature of the metal in the loop is higher than that of the metal in the main vessel, which limits the operating temperature of a Channel furnace since a high loop temperature shortens the life of the refractories of the loop. This means that their used for melting is restricted to low-temperature metals.

## **The Coreless Induction Furnace**

In a coreless furnace, the coil surrounds the entire charge, so the configuration is less complex. The mass of refractory is much less than in the channel furnace while the shape is a simple hollow cylinder. Hence coreless furnaces are much simpler and less costly to reline, although they require more frequent relines. The coreless furnace can be designed to operate at any frequency from 50Hz upwards.

Induction heating of liquid metal causes a stirring effect in the metal. The lower the frequency of the primary current, the more intense is the stirring. Melt compositions can be adjusted at any point in time during the melting cycle unlike in cupola where adjustment can only be effected on the charge make up. The stirring effects of this furnace help to remove compositional gradient.

## **ROTARY FURNACES**

These are simple hollow horizontal cylindrical furnaces lined with refractory material. It is a fuel-fired furnace and air for combustion is obtained from a blower powered by electric motor. It is incorporated with a rotating device and a smoke box. A burner is attached for the heating operation. The melting rate is high and the only limitation in the use of this furnace is that clean metal, free of impurities cannot be guaranteed, since the combustion products mix with the liquid metal.

## CRUCIBLE FURNACES

Crucible furnaces are vertical channel furnaces, having the body made up of steel shell of required thickness. The shell is lined with refractory while the crucibles can be fixed or removable. The melting rate is low but clean metal, free of intrusions can be obtained.

### **2.6 Nodularization**

Addition of elemental magnesium into an iron melt is normally very dangerous and delicate to handle. The first method of introducing magnesium to iron was to use pure magnesium for example introducing it in the form of wire through a refractory chamber at the bottom of the treatment ladle. Difficulty was then found with the very abrupt evaporation of this element, which has a vapour pressure which rapidly increase with temperature.

This has led to the use of pressurize ladle called the Grandpierre process or a sealed ladle, (Decrop, 1983). Other methods have been developed to slow down vaporization of magnesium and to increase the yield. Perhaps the most widely used method is the Mg-coke. This product consists essentially of pieces of coke, the pores of which are thorough impregnated with magnesium. This product, placed in the ladle under a grating-type double bottom (or introduced with a plunger) reportedly gives a magnesium yield of 40%. There would possibly be a carbon gain

of up to 0.15%. (Decrop 1983) The coke can be impregnated after use by heating to a high temperature 1100<sup>0</sup>C and immersing it in a bath of liquid Mg.

Another variation is a process developed by pont-a-mousson (Decrop, 1983). It involves the coating of a magnesium slab with an aluminosilicate refractory with different thickness on different faces in order to produce stepwise reactions using a plunger. Reaction is initiated at the uncoated end of the slab. It then continues at a controlled rate because of the refractory coating. Magnesium recovery ranging from 30 to 65 percent is possible depending on treatment temperature and ladle sizes.

At present, alloys are most often used, the oldest of which is the NICKEL-MAGNESIUM, which has the advantage of high density and therefore easily penetrates into the liquid metal. If present in low concentrations in iron, nickel cannot change the structure to any great extend but normally tends to promote pearlite formation. When present in high concentration as in table below, serve both as an alloying element to promote graphitization as well as stabilizing pearlite

**Table 1: Nikel-base Nodularizers (Hassan,2000)**

Trade name	Analysis %				
	Mg	Si	C	Fe	Ni

Incomag (Alloy 1)	13-16	-	2.0	-	Bal
Incomag (Alloy 2)	13-16	26-33	-	5 max	Bal
Incomag (Alloy 3)	4.2-4.8	-	2.0 max	-	Bal
Incomag (Alloy 4)	4-4.5	-	2.5 max	32-36	Bal

Silicon addition to nickel-magnesium alloy in alloy 2 serves primarily to reduce overall alloy cost and secondly as a source of silicon for the melt. Alloy 3 and 4 are characteristics of the newer generation of nodularizing materials. Recoveries of magnesium when using these materials are of the order of 80% to 90%.

Alloys 3 was developed primarily to provide a materials which produces a minimum amount of magnesium oxide fume while Alloy 4 was the result of further modification and improvement. It has an improved nickel magnesium ratio and the substitution of iron for a portion of the nickel lowered its density slightly (David, 1975).

At present, ferro-silicon-magnesium type products are most often used, these being lighter but more economical and obviating a nickel addition to the iron. The technique has developed the use of alloys with lower Mg contents, which allow calmer reactions and a better yield but they also increase the quantity of alloy used and therefore the Silicon introduced which makes it necessary to aim at a lower Silicon content in the burden.

The use of Fe-Si-Mg alloy requires certain devices to ensure that the alloys are introduced to the iron with a suitable yield. A more recent and more convenient method, the SANDWICH treatment method is essentially the same as the Tundish cover method but carried out in an open ladle (Foseco Handbook, 1994).

The magnesium alloy is placed in a pocket or cavity in the bottom of the ladle and covered with steel plate 2-3% of the metal weight. The molten metal stream is directed away from the cavity. The cavity must be deep enough to contain the entire alloy and the steel scrap, which should be of small size to promote a high packing density.

The treatment ladle is usually deep with a height to diameter ratio of 1.5 – 2.0:1.0. The extra metal depth increases the yield of the magnesium, which can be as high as 70% when a 5% Mg alloy is used. Due to the simplicity of the device this process is now becoming widespread.

### **2.6.1 Inoculation**

The magnesium treatment tends to promote the formation of carbide and the iron obtained would have a strong tendency to solidify “white”. It is therefore necessary to carry out inoculation with a graphitizing product (of the ferro-silicon type).

Inoculation treatment is not permanent; the effect begins to fade from the time the inoculants are added. As the inoculating effect fades the

number of nodules formed decreases and the tendency to produce chill and mottle increases. In addition the quality of the graphite nodules deteriorates and quasi-flake nodules may occur.

Apart from silicon, certain supplementary elements are also useful in the composition of inoculants; aluminum and calcium for example intensify the effect obtained, which would be weak with pure silicon.

From the thermodynamic data aluminum and calcium form carbides with a medium affinity of formation slightly stronger than that of Silicon carbide. It therefore seems that Aluminum and calcium replaced some of the Silicon in the carbide thus prolonging its existence. Aluminum and calcium could promote the presence of the carbide phase without completely stabilizing it (Decrop, 1983).

Inoculants for ductile iron must be added after the magnesium flare has subsided. A common practice involved tapping about half the metal onto the magnesium alloy and wait for the flare to finish before adding the inoculants to the tapping stream as the rest of the metal is tapped. Significant fading occurs within five minutes of inoculation. Because of this problem, late stream or mould inoculation is commonly used in ductile iron production.

Some alloys used in practice for inoculation is given in the Table 2.

**Table 2: Ferrosilicon Inoculants (Hassan 2000)**

Inoculants Alloy	% Si	% Ca	% Al	Other elements
75% Ferro-Silicon	74 – 79	0.5	1 – 3	-
ZL 80 (1)	80	2.5	1.2 – 1.5	Zr 1.5 – 1.7
ZL 80 Special (1)	-	-	2 – 3	Cast in a metal mould
Vp 205 (2)	75	1.4	4.4	MG 3
SUPERSEED (3)	72 – 77	None	0.5	Sr 0.6 – 1%, Mn 0.5%
602 (3)	69.5±1	2± 0.25	1.1±0.2	Zr 1.25 ± 0.25
Ferro-Silicon-Calcium-Zirconium (4)	65	5-7	0.1	Zr 5 – 7%
INOBAR (4)	60 - 65	1	0.5 – 0.8	Ba 9 – 11%

About 75% Ferro-Silicon, which generally contains a little calcium and aluminum is most widely used inoculants, the content of the later element must be limited in order to reduce the risk of pinholes.

Alloy ZL 80, Ferrosilicon contains calcium, zirconium and aluminum with a specially formulated composition kept within a narrow scatter range for inoculation. Alloy VP 205, 75% Ferro-Silicon containing calcium, aluminum, a little magnesium and cerium (0.07), and alloy 602, 70% Ferro-Silicon containing a little calcium and zirconium, with a limited aluminum content.

Supersede manufactured by Union Carbide to a (British Cast Iron Research Association) patent. This product would be more suitable than the previous

one for SG iron. It is a 75% Ferro-Silicon with a low aluminum content, no calcium, and containing a little strontium. With this composition, it is possible to reduce the risk of pinholes due to traces of aluminum.

### **2.7.0 Applications of Ductile Iron**

Ductile cast irons have replaced grey iron malleable iron and steel castings in many application giving better performance often at lower cost (QIT, 1983). Ductile iron castings can virtually always replace heavy welded steel fabrications up to medium size. Table 3 shows various engineering uses of ductile cast iron.

Table 3: Show Various Engineering Uses Of Ductile Cast Iron  
(QIT Fer et, 1983)

### **2.7.1 Effect of Various Elements in Nodular Cast Irons**

Carbon, silicon, magnesium, and cerium are elements generally present in all nodular cast irons. However, chromium, nickel, copper and molybdenum are major and common additions to nodular cast irons to promote special properties. In the same vein, impurity elements that are prevalent and must be controlled include phosphorus and sulphur.

Carbon is the most important element in nodular cast iron, and the level in the melt greatly influences its structure either in combined form as carbides, or as free graphite, and hence the grade of cast iron produced. Although the level of carbon does not directly affect properties, its indirect influence through its solubility in austenite plays an important role during casting solidification and cooling processes. The presence of carbon in an iron casting in the combined form increases its strength, shrinkage, chilling tendency, and in molten state, the cast iron fluidity is decreased Boyen et al (1984). In contrast, the presence of carbon in graphite form increases its fluidity.

Silicon is a strong graphitizer and its presence is responsible for precipitation of excess carbon as graphite in the melt and improve castability. Hassan (2002) demonstrated the proneness of nodular cast iron to sponge (interdendritic) shrinkage defects, when the ratios of carbon and silicon are not properly controlled. They provided a guide of the necessary

combination of carbon and silicon in the ranges of 3-4% and 2-3.5% respectively, to achieve optimum feeding characteristics.

The strong graphitizing effect of silicon stems from its effect on reducing the solubility of carbon in austenite, resulting in suppressing the formation of eutectic carbides, as well as accelerating the break down of eutectoid during mould cooling and heat treatment. While promoting ferrite formation and strengthening in nodular iron castings, the amount of silicon should be limited to levels less than 3.-% if toughness should be maintained. Beyond this level, the brittle-ductile transition temperature is significantly raised.

Manganese has a greater affinity for sulphur than iron. Its presence in iron castings will minimize the formation of iron sulphide (FeS) which has a hardening and embrittling effect on iron castings. It is the usual practice to have manganese contents in excess of the stoichiometric requirement to ensure that the sulphur has completely combined with manganese. For practical purposes, the following empirical formula is normally satisfied.

$$\%Mn = 1.7\% S + 0.3\% \text{ (Hassan, 2002) ----- (2)}$$

Manganese, in excess of the amount required for controlling the sulphur level in the melt, increases the strength, hardenability and hardness of nodular iron castings. In this respect manganese is a mild carbide former and an austenite stabilizer. Manganese has an undesirable property of segregating into the last liquid metal to solidify and this promotes carbides

in grain boundary areas of slowly solidified sections. This behaviour necessitates the control of amount of manganese, which should be preferably limited to levels less than 0.3% in base irons intended to produce heavy nodular cast iron sections and for casting that will be subjected to austempering treatment (Hassan, 2002).

Magnesium is primarily used as a nodularizing agent in nodular iron production. It can function as a desulphurizer when introduced into molten iron and decreases the tendency to form iron carbide in iron castings.

Chromium is a moderate carbide former and intensifies the chilling tendency in iron castings. Chromium promotes the formation of more finely laminated and harder pearlite, thus increasing the strength, hardness and wear resistance of the cast iron matrix. In amounts of 1.0 to 3.0%, it adds resistance to softening and scalling at temperatures up to 760°C. it is also effective in preventing retard graphitization in heavy sections. Chromium is frequently used in combination with nickel, copper and molybdenum for optimum mechanical properties.

Solubility of copper in cast iron is reported to be of order 3.5%, whereas, a maximum solubility in ferrite iron is only 1.4% (Hassan, 2002). Copper is also reported to be a mild graphitizer, austenite stabilizer, matrix toughener and its has a desirable property of increasing molten iron fluidity.

Nickel forms solid solution in all ferrites in cast irons and it is used in conjunction with other alloying elements, such as copper, molybdenum and

manganese in the production of nodular cast irons with ferritic-pearlitic, acicular-bainitic and martensitic matrix structures to provide general mechanical properties. It is usually found in pearlitic-ferritic grades for strength, toughness and to promote casting hardenability. Like silicon, it promotes graphitization (Hassan, 2002).

Molybdenum is a strong carbide former and its addition beyond low levels will reduce the graphitizing effect of silicon and promote chilling in iron castings. Molybdenum is usually added to nodular iron castings to improve hardenability as well as to increase strength, hardness and structure homogeneity, particularly in heavy sections. Molybdenum is also included in iron castings to improve performance in applications requiring high temperature strength and good wear resistance. Molybdenum is effective in controlling the as-cast structures (Hassan, 2002).

## ALLOY IRON CASTINGS

Alloy cast irons fall into either graphite-free or graphite-bearing grades. The graphite-free grades are white cast irons, which are selected to resist corrosion or for high resistance to wear especially at elevated temperatures. These alloy white cast irons are employed as pumps and piping for corrosive liquids, valves and fittings for steam dryers, valve steam bushings, valve and pump bodies in petroleum and manifolds (Hassan, 2002).

The graphite bearing alloy cast iron are for improved creep strength, dimensional stability at high temperatures, high resistance to thermal shock, oxidation and scalling. Common commercial alloy cast irons include:

1. Heat-resistant cast irons
2. Wear-resistant cast irons
3. Corrosion-resistant cast irons
4. Special purpose cast iron

The resistance to softening depends to a large extent on presence of microstructures in which carbon does not precipitate easily and resistance to scalling depends on the formation of a protective oxide film on the surface on exposure to oxidizing condition.

The composition of heat resistant cast irons varies in a wide range, but most of these contain nickel, chromium and silicon as the principal alloying elements, and molybdenum, copper and aluminium as minor elements. The microstructure of these irons are normally ferritic or austenitic in the as-cast state. The ferritic grades include irons which contain up to 5% silicon (“Sikal” Grades) and high chromium types. The austenitic grades are Ni-base, and examples of these are “Ni-Resist” and “Nicrosilal” (Hassan, 2002).

Grey irons are used under lubricative and dry sliding conditions. In these conditions, sliding contact under load is continuous as in bearings or reciprocating as with pistons contained in cylinders. The relationship

between microstructure and wear resistance is complex, but wear resistance is improved if the cast iron is fully pearlitic or martensitic. Martensitic matrix displays higher wear resistance than pearlitic matrix structure. The use of nodular iron crankshaft is an example in this respect.

Cast irons derive their corrosion resistance mainly from their chemical analysis and the distribution of alloying elements within the microstructure which may comprise a ferritic, pearlitic, martensitic, or austenitic matrix. Most materials which exhibit good corrosion resistance are also reported to give good heat resistance. Other corrosion resistant cast irons include those containing high silicon content (12-18%) and high alloy irons are non-magnetic grades. They are known as “Nomag” irons (Hassan, 2002). These are basically austenitic but their non-magnetic properties are controlled by the composition in respect of presence of combinations of alloying elements which include nickel, silicon, manganese, copper and sometimes aluminium.

## CHAPTER THREE

### EXPERIMENTAL METHODS

#### 3.1 MATERIALS

The materials used for this research work some of which were obtained from Bamfords International foundries Jos include: High purity sorrel pig iron, Ferro Silicon, Magnesium Ferrosilicon, Ferro Molybdenum, Ferro Vanadium.

The chemical compositions of the experimental raw materials are given in Tables 3.1 to 3.4 as obtained from material test certificates.

Table 3.1: Sorrel pig iron used

%C	%Si	%Mn	%S	%Pb	%P
4.08	0.92	0.05	0.019	0.034	0.04

Table 3.2: Ferro-silicon used

%Si	%Al	%C	%S	%P
75	0.31	0.0032	0.001	0.001

Table 3.3: Ferro-molybdenum used

%Mo	%C	%S	%P
72.23	0.016	0.025	0.025

Table 3.4: Ferro Vanadium used

%V	%C	%S	%Si	%Al	%Cu	%P
79.90	0.20	0.04	1.03	1.10	0.02	0.02

### 3.2 EQUIPMENT

The equipment used in this research include a 100kg fuel fired rotary furnace, two 3kg ladles, 25mm diameter pipe, immersion pyrometer, metallurgical microscope with built in camera, tinus-olsen testing machine, Avery Denison impact testing machine, Rock-well hardness tester, grinding and polishing machine, heat treatment furnace and digital weighing scale.

### 3.3. METHODS

The alloyed ductile iron samples that were used in this study, were produced using sandwiched treatment method at the foundry shop of the Metallurgical Engineering Department, Ahmadu Bello University, Zaria Nigeria. The samples were produced by varying the percentage additions of vanadium and molybdenum from 0.1- 0.3% respectively. Where the percentage additions of vanadium were fixed at 0.1%, percentage addition of molybdenum was varied from 0.15 to 0.3. Similarly when the

molybdenum addition was fixed at 0.1%, vanadium addition was varied from 0.15 to 0.3%.

The base metal was melted in the rotary furnace after a careful material charge balance (calculation) as shown in Table 3.5, prior to alloying and ladle modularization treatment, ferrosilicon addition was added after the pig iron has been melted and vigorously stirred.

Table 3.5: Material charge calculation

Material	Amt (kg)	%C	%Si	%S	%P	%Mn	%Al
Sorrel (pig iron)	70	4.08	0.92	0.019	0.034	0.05	-
Ferro silicon	0.55	-	0.589	-	-	-	0.003
Total		4.08	1.509	0.019	0.034	0.05	0.003

The molten metal was maintained at a composition of 3.88%C and 1.4% Si prior to ladle treatment.

Table 3.6: Ferro Molybdenum charge addition

Material	Amt (kg)	%C	%Si	%Mo	%V	%s	%p

A	0.004	0.0002	0.00127	0.10	0.1	-	-
B	0.0062	-	-	0.15	0.1	-	-
C	0.0083	-	-	0.20	0.1	-	-
D	0.01038	-	-	0.25	0.1	-	-
E	0.01246	-	-	0.30	0.1	-	-

Table 3.7: Ferro vanadium charge addition

Material	Amount (kg)	%C	%S	%Si	%V	%Mo
A	0.00375	-	-	-	0.10	-
B	0.0056	-	-	-	0.15	0.1
C	0.0075	-	-	-	0.20	0.1
D	0.0093	-	-	-	0.25	0.1
E	0.01126	-	-	-	0.30	0.1

3.75gm of ferrovanadium was added to sample B through sample E on Table 3.6 to keep Vanadium at 0.1 percent, while 4.15gm of Ferromolybdenum was added to sample B through sample E on Table 3.7 to keep Molybdenum at 0.1 percent

The sandwiched ladle treatment method which involved covering the alloy containing the magnesium (Magnesium Ferro silicon) in a portion of

the ladle with some clean sheet of metal of about 2mm thick and 1.5% by weight of the metal to be treated was used.

Ferro-molybdenum and vanadium were also added in the ladle according to the various specifications. The base metal, which was at 1450<sup>0</sup>C at the time of pouring, was directed away from the covered alloy until it finally engulfed the alloy. The magnesium reaction lasted for only 10-15sec.

The ferrosilicon magnesium has a magnesium content of 5% to allow calmer reaction and a better yield, but they also increase the quantity of alloy used and therefore the Silicon introduced which makes it necessary to aim at a lower silicon content in the charge.

Since the magnesium treatment tends to promote the formation of carbide and the iron obtained tends to solidify “white”, inoculation with a graphitizing alloy such a ferrosilicon was carried out during pouring.

Depending on the sulfur content of the base metal the amount of magnesium used in kg was determined from the Emperical equation (Mikhailov, 1989 and Decrop, 1983).

$$Q = p \frac{0.76(s - 0.01) + k + t \times 10^{-3} \left[ \frac{T}{1450} \right]^2}{R \times Mg / 100} \dots\dots\dots (3)$$

Where Q - the quantity of magnesium alloy to be used in kg  
P - weight of iron to be treated

- S. - Sulphur content in the base iron
- t - Dwell time in Min for the iron after treatment and before Casting.
- T - Temperature of the iron at time of casting in °C.
- R - Expected magnesium yield from the operation in %
- Mg - Magnesium rate in the alloy used.
- K. - target residual magnesium content.

The treated metal was poured into the sand mould as test samples.

Unalloyed test samples were also produced to serve as control and for some selected heat treatment processes.

2.5% by weight of the base metal was the amount of magnesium ferrosilicon used in the treatment, and the elemental contribution to the base metal is shown in Table 3.8.

Table 3.8: Ferro Magnesium and Ferro silicon charge

<b>MATERIAL</b>	<b>AMOUNT IN (gm)</b>	<b>%Mg</b>	<b>%Si</b>
MgFe Si	75	0.125	1.2

Fe Si	4	-	0.1
	Total	0.125	1.3

### **3.4 HEAT TREATMENT**

The unalloyed test bars were machined into tensile impact and hardness samples before being subjected to heat treatment. Normalizing, quenching and tempering heat treatment processes were carried out.

#### **3.4.1 NORMALIZING**

This treatment method was selected to ensure entirely a pearlitic structure. The samples were heated to 900<sup>0</sup>C and held for 1hr. This was followed by cooling in air.

#### **3.4.2 QUENCHING AND TEMPERING**

The samples were also heated to 900<sup>0</sup>C and rapidly quenched in water. Reheating the samples to 350<sup>0</sup>C followed this. The samples were finally cool to room temperature under the furnace atmosphere.

### **3.5 MECHANICAL PROPERTIES DETERMINATION**

#### **3.5.1 Tensile Strength Determination**

The tensile strength of the machined samples were determined using a tensile machine. The test began by first of all making the specimen gauge length with pink punch mark, then measuring the X- sectional area of the reduced section.

The specimen was then locked securely in the grips of the upper and lower cross beam of the testing machine. A small load was initially applied to seat the specimen; load was gradually increased until failure occurred.

The ultimate tensile strength (*UTS*) was determined from the relationship

$$UTS = \frac{P_{max}}{A_0} \dots\dots\dots (4)$$

$P_{max}$  is the maximum load in Newton before failure occurred while  $A_0$  is the original X- sectional area of the reduced section in (mm<sup>2</sup>).

### 3.5.2 Yield Strength Determination

The conventional denoting 0.2% offset was used in determining the yield strength. Selecting 0.002mm by scale and drawing a line parallel to the elastic or linear portion of the load- extension curve. The intersection of this line with the load – extension curve gave the yield load  $p_y$  and the ration of the yield load to the original x-sectional area  $A_0$ . gave the yield strength.

$$D_Y = \frac{P_Y}{A_0} \dots\dots\dots (5)$$

### 3.5.3 Percentage Elongation Determination

This data was determined by fitting together the broken halves of the specimen and measuring the distance between the original gauge marks and then it was estimated from the relationship, below (Davies, 1983).

$$\%E = \frac{L_f - l_0}{L_0} \times 100 \dots\dots\dots (6)$$

Where  $L_f$  = final gauge length

$L_0$  = Original gauge length

### **3.5.4 Hardness Values Determination.**

The hardness values of the samples were determined using the Rockwell hardness tester on ‘c’ scale with diamond pyramid cone indenter, minor load of 10kg and major load of 150kg.

A standard sample having a hardness of 5.79HRC was initially tested. The test samples were placed one after the other on the table of the machine and the indenter is brought into with the prepared surface under a minor load of 10kgf. This takes up the slack in the system and the dial indicator is set to zero, the major load is then applied. When the reading of the dial indicator was ready, the major load is taking off. The test-piece remains under the minor loads while the hardness value is read directly from the dial indicator. Several readings were taken on each sample before an average values were calculated.

### **3.5.5 Impact Strength Determination**

The impact test was carried out according to the recommended standard charpy v-notched method. Before the test, the pendulum was released to zero the scale. The test bar, which has a dimension 75mm by 100mm, was then gripped horizontally in a vice, the force needed to break the bar was released from the pendulum of the machine through an angle. The value of the angle corresponds with the value of the energy absorbed in breaking the sample on the machine. The reading was then recorded and the results are shown in Tables A1 and A2

### **3.5.6 Metallographic Analysis**

Both the as-cast alloyed and the heat treated samples were prepared for metallographic examination. Normal method of specimens preparation for microstructure examination was adopted for metallographic samples mounted in bakerlite using the usual grades of silicon carbide abrasive papers (240 to 600 grits) sizes. Following the polishing operation, etching of the polished specimen was done using 2% Nital (consists 2% Nitric acid,  $\text{HNO}_3$  in ethyl alcohol). The structure obtained were photographically recorded using metallurgical microscope with built-in camera. The photographs are shown in micrographs B1 to B13.

Table 3.9: Spectrometer analysis of Vanadium alloyed Ductile Iron  
Produced

<b>S/NO</b>	<b>C</b>	<b>Si</b>	<b>Mn</b>	<b>S</b>	<b>P</b>	<b>Mg</b>	<b>Mo</b>	<b>V</b>
1	3.85	2.7	0.05	0.015	0.04	0.02	8	0.1
2	3.82	2.7	0.05	0.015	0.04	0.02	0.1	0.15
3	3.86	2.7	0.05	0.015	0.04	0.02	0.1	0.201
4	3.85	2.7	0.05	0.015	0.04	0.02	0.1	0.249
5	3.80	2.7	0.05	0.015	0.04	0.02	0.1	0.302

Table 3.10: Spectrometer analysis of Molybdenum alloyed Ductile cast iron  
Produced

<b>S/NO</b>	<b>C</b>	<b>Si</b>	<b>Mn</b>	<b>S</b>	<b>P</b>	<b>Mg</b>	<b>Mo</b>	<b>V</b>
1	3.82	2.7	0.05	0.015	0.04	0.025	0.109	-
2	3.87	2.7	0.05	0.015	0.04	0.025	0.149	0.1
3	3.80	2.7	0.05	0.015	0.04	0.025	0.200	0.1
4	3.79	2.7	0.05	0.015	0.04	0.025	0.25	0.1
5	3.81	2.7	0.05	0.015	0.04	0.025	0.38	0.1

## **CHAPTER FOUR**

### **4.0 RESULTS AND DISCUSSION**

#### **4.1 RESULTS**

The results that were obtained from this research work are presented in tables A1 to A3 and figures B1 to B12. The microstructures developed of plain, alloyed and heat-treated ductile iron samples are shown in micrographs 1 to 13. The mechanical properties obtained of both unalloyed, alloyed and the heat-treated plain ductile cast iron samples are entered in tables A1 to A3. The graphs of the effect of vanadium, molybdenum additions on the mechanical properties of ductile cast iron samples are shown in Figures B1 to B10.

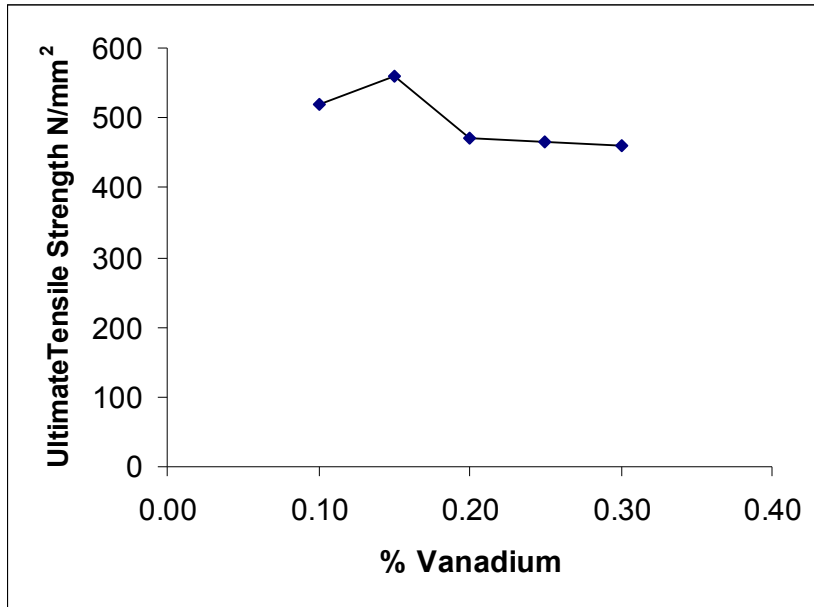


Figure 4.1: Effect of Vanadium Additions (0.1Mo) on the Tensile Strength of Ductile Iron

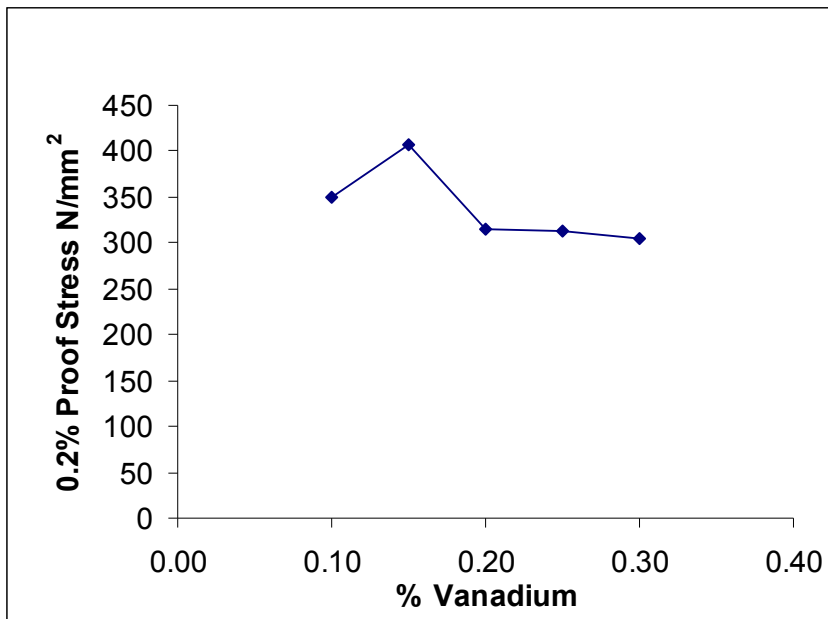


Figure 4.2: Effects of Vanadium Additions (0.1Mo) on Proof Stress of Ductile iron

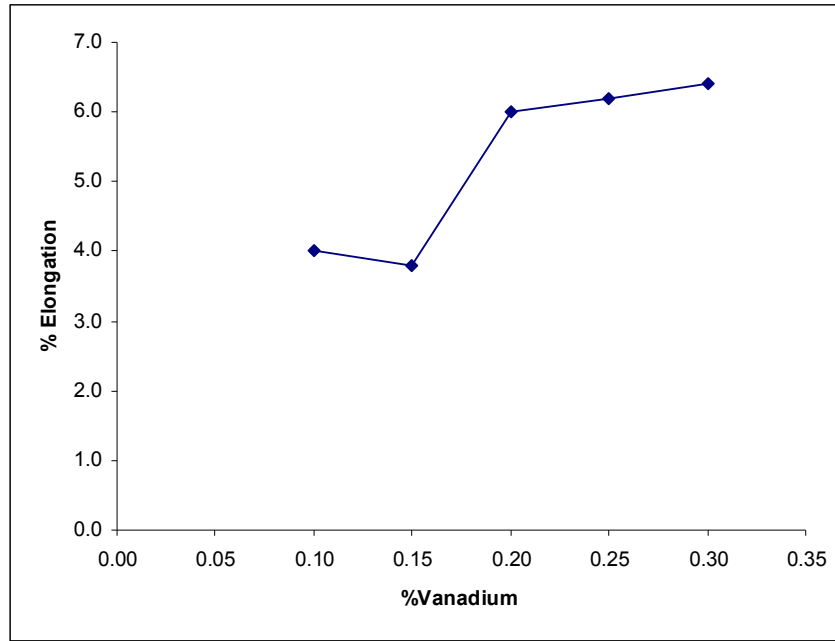


Figure 4.3: Effect of Vanadium Additions (0.1Mo) on %Elongation of Ductile Iron

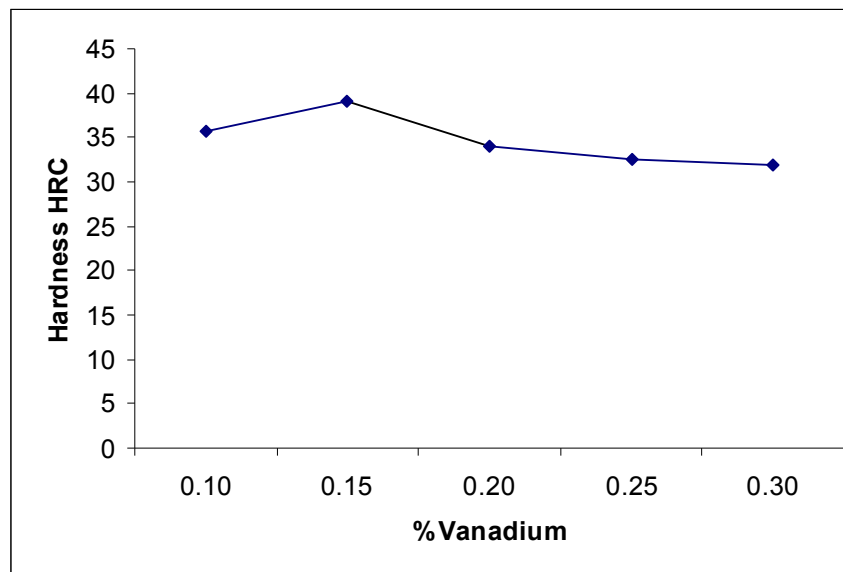


Figure 4.4: Effect of Vanadium Additions (0.1Mo) on Hardness of Ductile Iron

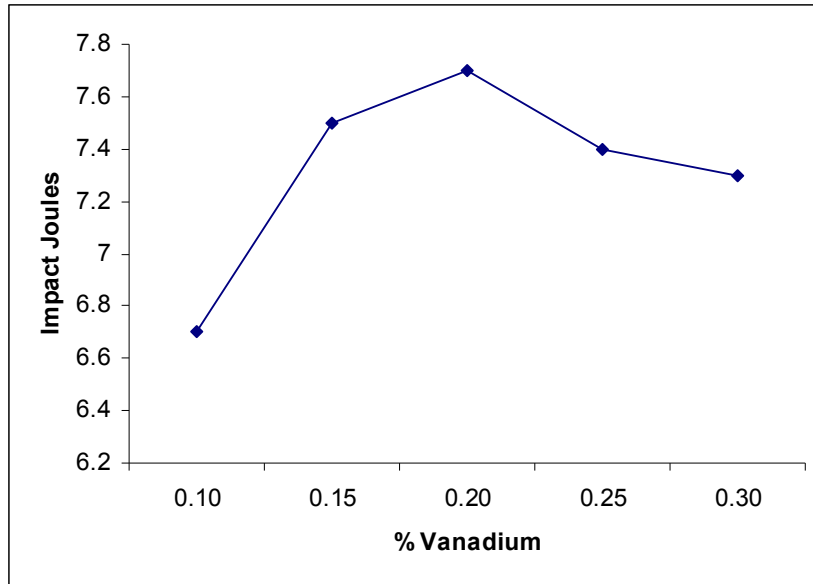


Figure 4.5: Effect of Vanadium Additions (0.1Mo) on Impact properties of Ductile Iron

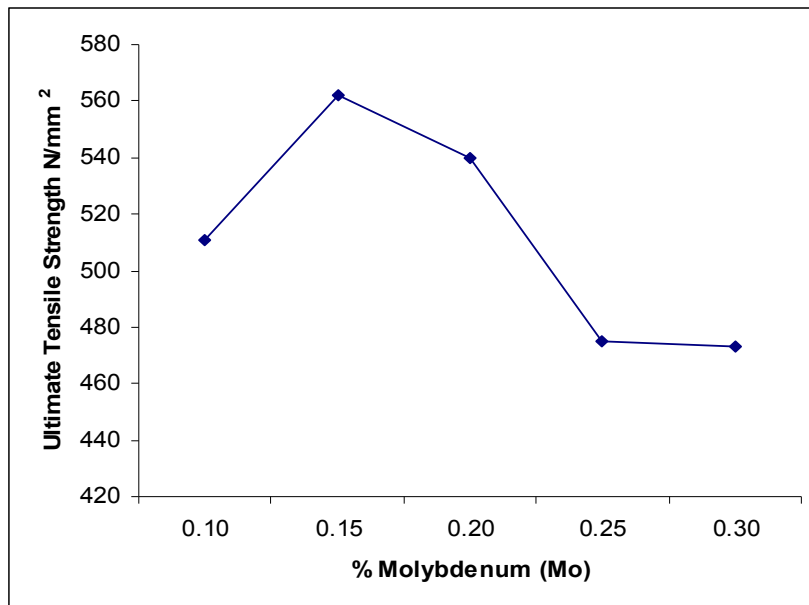


Figure 4.6: Effect of Molybdenum Additions (0.1V) on the Tensile Strength of Ductile Iron

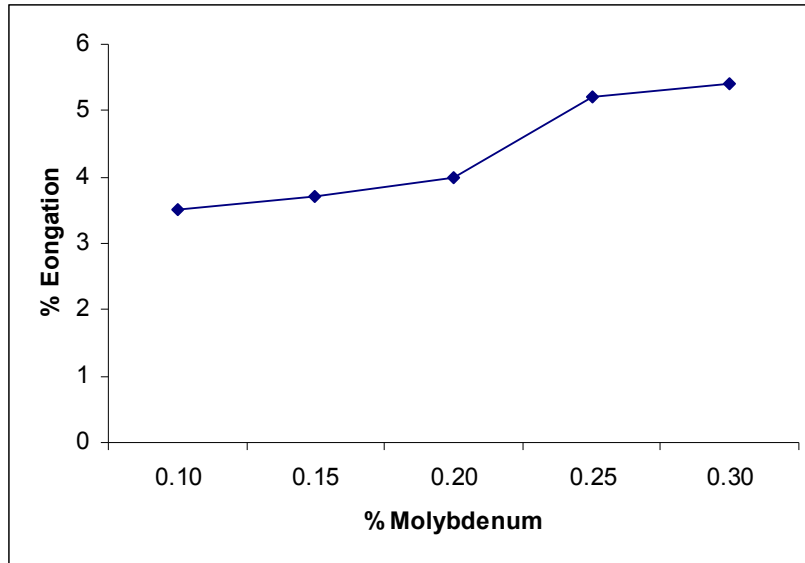


Figure 4.7: Effect of Molybdenum Additions (0.1V) on % Elongation of Ductile Iron

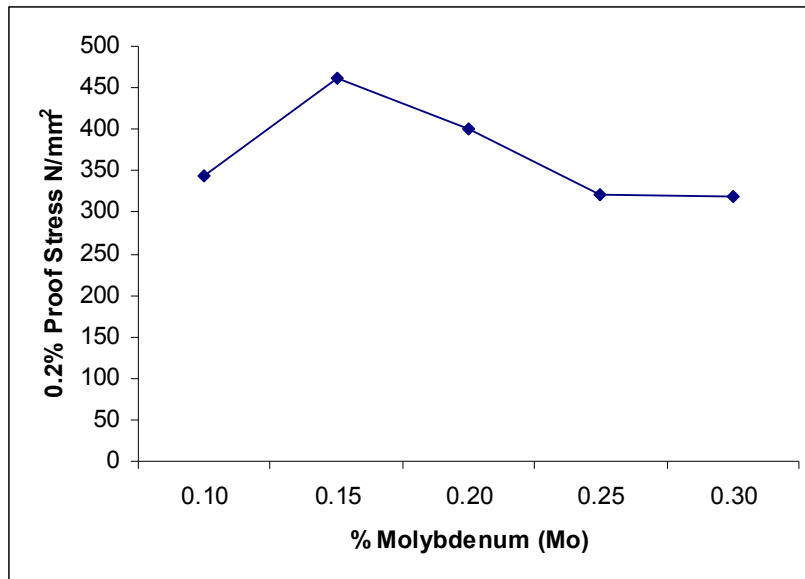


Figure 4.8: Effect of Molybdenum Additions (0.1V) on 0.2% Proof Stress of Ductile Iron

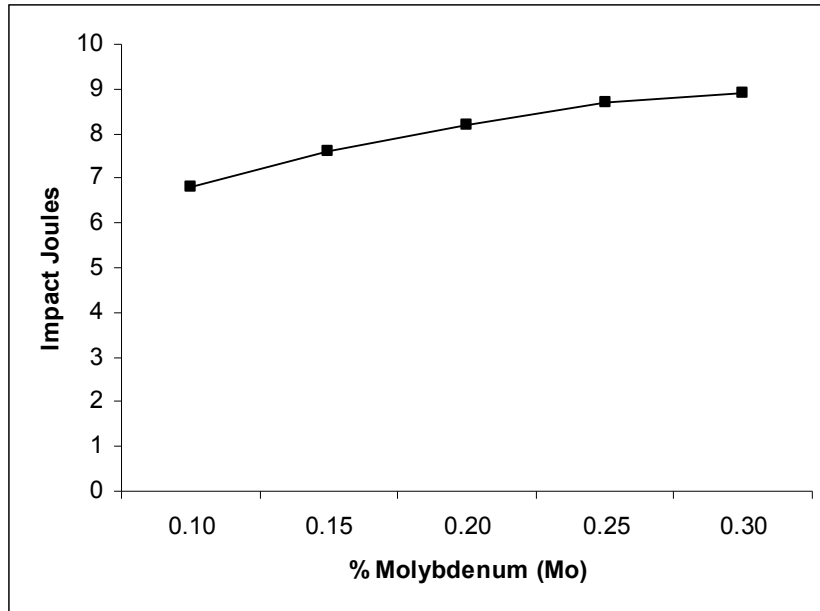


Figure 4.9: Effect of Molybdenum Additions (0.1V) on the Impact Energy of Ductile Iron

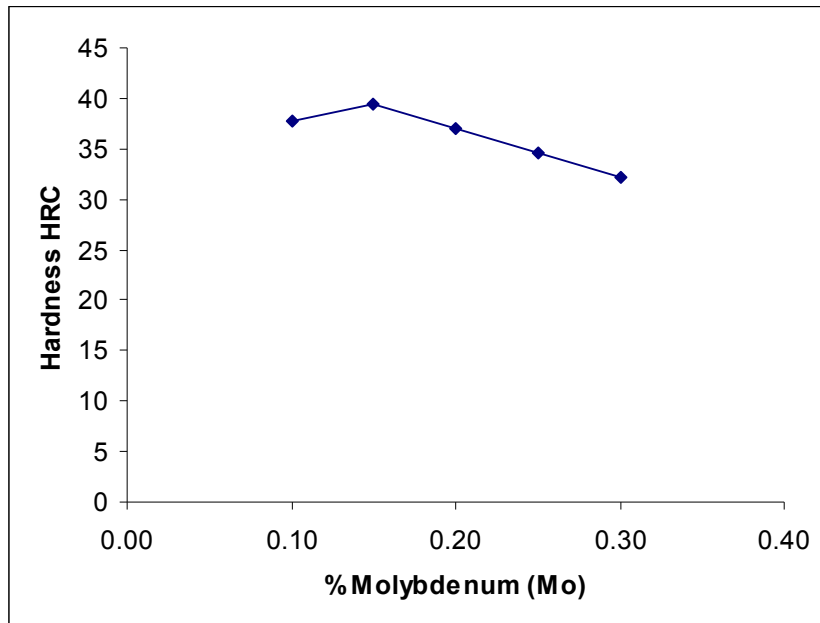


Figure 4.10: Effect of Molybdenum Additions (0.1V) on the Hardness of Ductile Iron

## **4.2 DISCUSSION**

### **4.2.1 Effects of Vanadium Addition on the Micro-Structures of Ductile Cast Iron**

The micro-structure of plain ductile cast iron which was cooled to room temperature in the mould is shown in micrograph B1. The microstructure consists of graphite nodules surrounded by ferrite rings resulting into a “Bull-eye” structure in a pearlitic matrix as expected.

The structure obtained when 0.1% vanadium was added to the ductile cast iron is shown in micrograph B2. The structure reveals ferrite rings surrounding the graphite nodules, with few pearlite and vanadium carbide.

As the amount of vanadium was raised to 0.15%, and 0.1% molybdenum as shown in micrograph B3, the structure shows a mix matrix of ferrite and pearlite with increasing proportion of pearlite. Ferrite surrounding nodules is still a constituent of the microstructure. More proportion of pearlite is observed than in the micrograph of the vanadium alloyed ductile iron. The observed difference is attributed to increase in the content of vanadium and the 0.1% addition of molybdenum. Further increase in the additions of vanadium yielded the microstructure shown in micrograph B4 to B6.

The observed phases present in the microstructures agreed well with research finding which revealed that these elements due to their “partitioning” effect retard rate of pearlite transformation resulting in

precipitates of fine vanadium and molybdenum carbides as cooling progress (Raghavan, 1989 and Dieter, 1988).

#### **4.2.2 Effects of Molybdenum Additions On The Microstructure Of Ductile Cast Iron.**

The structures obtained when molybdenum is added to ductile cast iron in the range of 0.1 to 0.3% are showed in micrographs B7 to B11. The structure consists of a combination of precipitates from solid solution, which account for the fine alloyed carbides particle and that of eutectoid structures. As the amount of molybdenum addition increases, there is observed increase in the proportion of ferrite and the alloyed carbides in the structures. This increase in the proportion of ferrite as the amount of molybdenum additions increases strongly suggests that the molybdenum stabilizes ferrites phase. (Raghavan, 1989).

#### **4.2.3 Effects of Vanadium Additions on The Mechanical Properties of Ductile Cast Iron.**

Table A1 shows the effect of Vanadium additions on the tensile strength, 0.2% proof stress,% elongation hardness and impact energy of ductile cast iron samples. From the table, all the mechanical properties investigated except percentage elongation and impact energy increase as the

percentage addition of V/Mo increased up to 0.15%. The percentage elongation and the impact values dropped within that range of addition.

Beyond 0.15% addition of vanadium and 0.1% of molybdenum, all the mechanical properties of alloyed ductile cast iron samples with the exception of impact and percentage elongation drop from the highest value which occurred at 0.15% vanadium and 0.1% molybdenum additions. However percentage elongation increased to value of 6.4 at 0.3% vanadium additions.

The increase in strengths and hardness can be attributed to grain refinement, presence of fine dispersed alloyed carbides of vanadium and molybdenum and the impediment of dislocation movement that are likely caused by these fine particles.

As shown in figures 4.1 to 4.5 all the mechanical properties except the percentage elongation increase up to a certain value and drop to the lowest values as the vanadium addition is increased. However percentage elongation drops up to certain value before rising as the vanadium addition is increased.

#### **4.2.4 Effects of Molybdenum Additions on The Mechanical Properties of Ductile Cast Iron.**

Table A2 shows the effect of Molybdenum additions on the tensile strength 0.2% proof stress, percentage elongation, hardness, and impact energy of ductile cast iron samples. From the table, the ultimate tensile strength and 0.2% off set yield and hardness values increased to a maximum when the molybdenum addition is 0.15% and further increase in molybdenum addition up to 0.3% and 0.1 vanadium resulted in a slight drop in values of these properties. The slight drop in properties particularly tensile may be attributed to a solidification phenomenon. The vanadium and molybdenum in excess of 0.15% are rejected to the center as solidification progresses, and eventually solidified at the grain boundaries as the solidification is completed. Since the grain boundary is a point of weakness, the tensile properties will therefore be affected. The impact and elongation value however showed a slight increase as the percentage addition of molybdenum increased to 0.3%. The initial increase in strength and hardness can be attributed to the presence of molybdenum and vanadium carbides particles in the structure that toughens the material.

As shown in figure 4.6 to 4.10, all the mechanical properties increased to their maximum values and dropped as a percentage addition of molybdenum increases with the exception of impact energy and percentage

elongation, whose value increased as the percentage molybdenum increases.

#### **4.2.5 Effects Of Heat Treatment On Microstructure And Mechanical Properties Of Plain Ductile Iron.**

Micrograph B13 shows the microstructure of normalized plain ductile iron. This microstructure consists of graphite nodules in a shell of ferrite in a completely pearlitic matrix. The microstructure of the plain ductile cast iron quenched and tempered consists of tempered martensite as evidence in micrograph B13.

Comparatively, the mechanical properties of the heat-treated plain ductile cast iron samples such as ultimate tensile strength, yield strength and hardness values are reasonably high and in some cases more than those of the V/Mo alloyed ductile iron. The elongation and impact values of the heat-treated ductile cast iron are however very inferior to all the grades of vanadium and molybdenum alloyed ductile iron investigated.

#### **4.2.6 Comparative Microstructure and Mechanical Properties.**

The microstructure obtained in both the vanadium treated and molybdenum treated ductile irons are slightly similar. While the phases in vanadium treated are finer than the molybdenum alloyed ductile iron, there are lesser amount of pearlite in the microstructure containing molybdenum

addition. This observed difference reasonably suggests that the partitioning effect of molybdenum as substitution element between the two phases that constitute pearlite appears to be more severe. This effect might have been responsible for the high proportion of the alloyed carbides.

Similarly, the increase in proportion of ferrite phase as the molybdenum addition increases can be attributed to compositional effect. Molybdenum is known to dissolve in ferrite and stabilize it. The minimum amount of molybdenum needed to increase the mechanical properties might have been exceeded, the excess went into stabilizing the ferrite, hence the observed decrease in mechanical properties (Ragavan, 1989). Also the impact value increases as the molybdenum addition increases. This result agreed reasonably well with previous research findings, (Metals Handbook, 1978 and Higgins, 1994).

## CHAPTER FIVE

### 5.0 CONCLUSION AND RECOMMENDATION:

#### 5.1 CONCLUSION

From the result obtained, the following conclusions can be made:

1. The microstructure of V/M<sub>0</sub> alloyed ductile cast iron gave good combination of toughness and strength.
2. The vanadium alloyed ductile cast iron samples developed impact values that increased up to 7.7 joules before decreasing to 7.3 joules with vanadium additions while molybdenum alloyed ductile cast iron samples gave impact values that steadily increased with molybdenum additions.
3. The differences observed between the two alloyed can be attributed to the fact that 0.15% of vanadium was just enough quantity needed to combine with molybdenum to produce the right strengthen alloy within the grades under investigation.
4. Ductile cast iron alloyed treated with vanadium containing 0.15%V, 0.1M<sub>0</sub> and ductile cast iron treated with molybdenum containing 0.15% possess the highest strength in the two alloys under consideration.
5. Ductile cast iron containing 0.2% molybdenum possessed the best combination of properties that can be specified for applications

requiring high strength, good wear resistances, moderate ductility and impact properties.

6. The heat-treated samples produced higher strength but poorer impact and elongation values. In some cases the yield strengths of some of the vanadium, molybdenum treated ductile iron are even higher making them more attractive for some applications.

## **5.2 Recommendations**

Following the results obtained from this study, it is obvious that the potentials of ductile cast iron as an engineering material are still undergoing development. The following recommendations are made:

1. The high temperature properties of these vanadium treated ductile cast iron should be further investigated considering the effect of vanadium in grain refinement.
2. Prototype parts such as camshaft thrust plate which is exposed to severe abrasion wear in service, Automotive clutch pressure plate exposed to heavy alternating loads which requires high strength, reliability and easy machining should be produced and tested.
3. The development and production of these Ferro alloys should be pursued with all the seriousness it deserved since they form the major raw material for these research findings.

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## APPENDIX A

Table A.1: Mechanical characteristics of ductile cast irons with vanadium additions.

<b>% V</b>	<b>% M<sub>o</sub></b>	<b>Tensile strength (N/mm<sup>2</sup>)</b>	<b>0.2% proof stress (N/mm<sup>2</sup>)</b>	<b>% Elongation</b>	<b>BH N</b>	<b>Impact Values (Joules)</b>
-	-	456	307	6.7	290	7.3
0.10	-	520	350	4.0	331	6.7
0.15	0.1	560	407	3.8	369	7.5
0.20	0.1	470	315	6.0	322	7.7
0.25	0.1	465	312	6.2	303	7.4
0.30	0.1	460	305	6.4	294	7.3

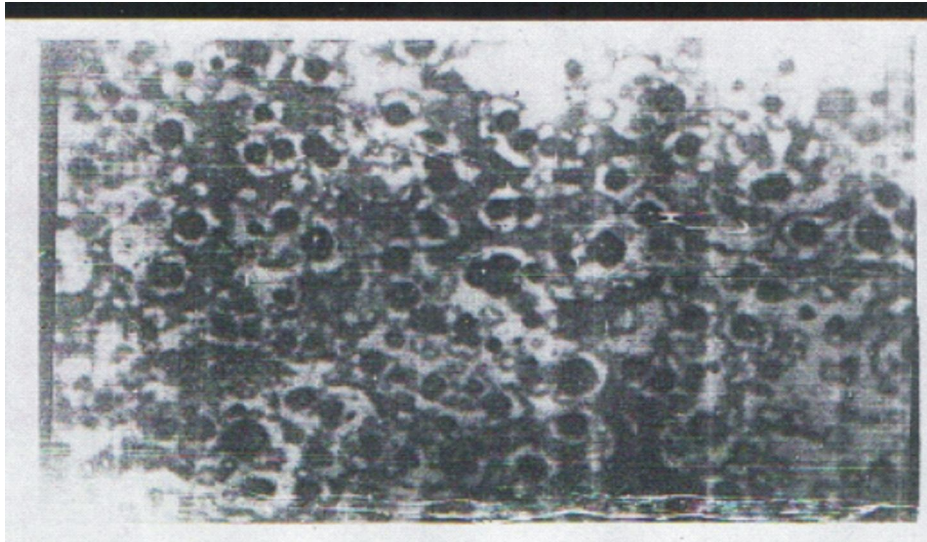
Table A2. Mechanical characteristics of ductile cast irons with Molybdenum additions.

<b>% M<sub>o</sub></b>	<b>% V</b>	<b>Tensile strength (N/mm<sup>2</sup>)</b>	<b>0.2% proof stress (N/mm<sup>2</sup>)</b>	<b>% Elongation</b>	<b>Hardness Values BHN</b>	<b>Impact Values (Joules)</b>
0.10	0.1	511	343.6	3.5	350	6.8
0.15	0.1	562	462	3.7	362	6.5
0.20	0.1	540	400	4.0	343	8.2
0.25	0.1	475	320.4	5.2	325	8.7
0.30	0.1	473	319	5.4	300	8.9

Table A3 Mechanical characteristics of Heat-treated Unalloyed Ductile cast iron.

<b>Treatment Methods</b>	<b>Tensile Strength (N/mm<sup>2</sup>)</b>	<b>0.2% proof stress (N/mm<sup>2</sup>)</b>	<b>Impact (Joules)</b>	<b>% Elongation</b>	<b>Hardness BHN</b>
Normalized	650	400	2.5	3.6	388
Quenched and Tempered.	700	460	3.0	2	369

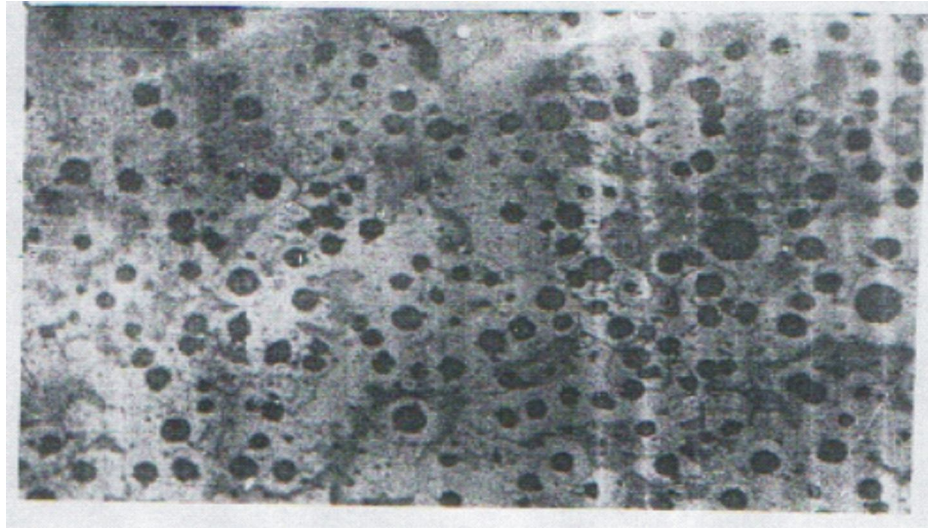
## APPENDIX B



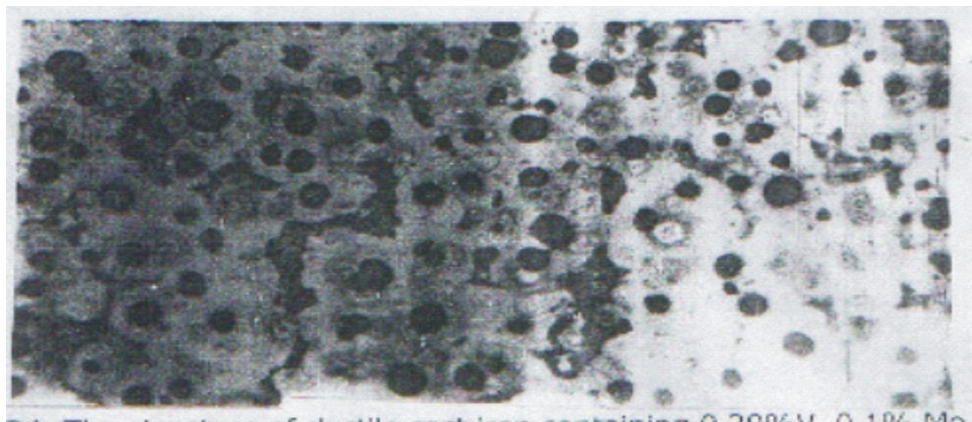
Micrograph B1: the structure of plain ductile cast iron. This microstructure shows graphite nodules (black ball) with ferrite rings (white) and few “Bull eye” structure in pearlite matrix (x 250).



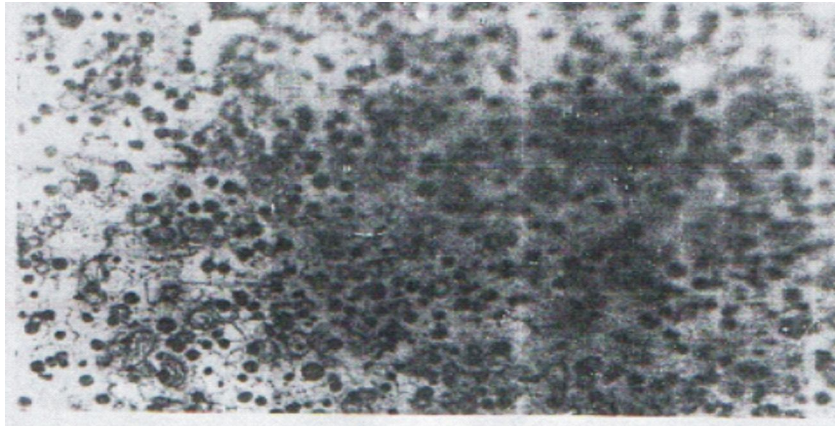
Micrograph B2: the structure of ductile cast iron containing 0.1%V addition. This microstructure shows graphite nodules (black ball) with fine precipitates of VC (grey) in a predominantly pearlitic matrix (x 250).



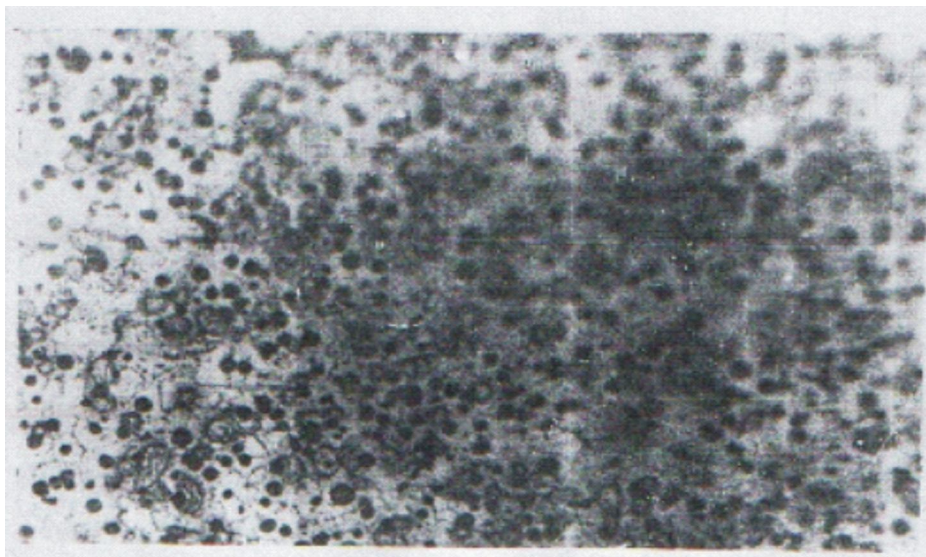
Micrograph B3: The structure of ductile cast iron containing 0.15% V, 0.1% Mo addition. This microstructure shows graphite nodules (black balls), with increasing proportion of fine precipitates of V, Mo carbides (grey) all in a matrix S(x 250).



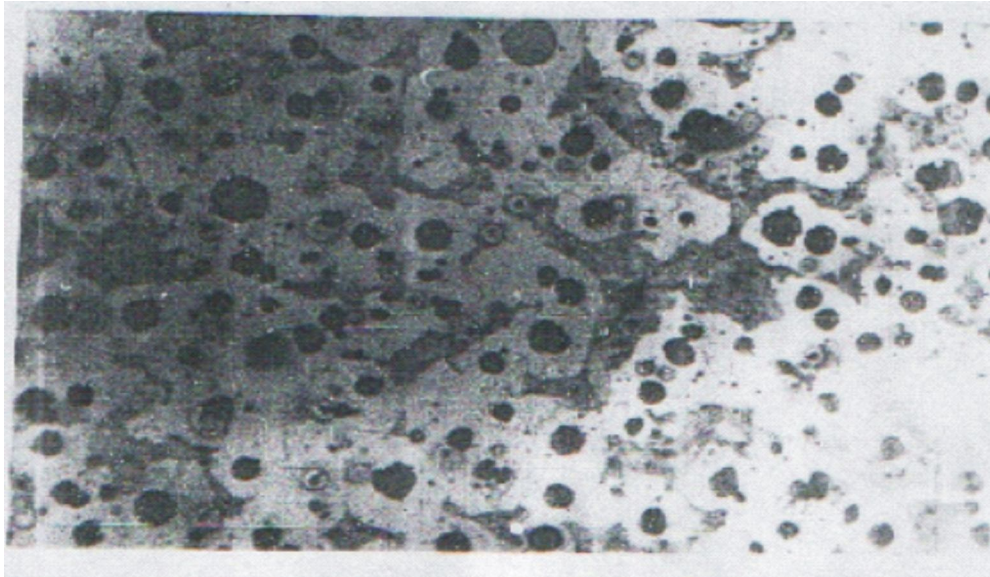
Microstructure B4: The structure of ductile cast iron containing 0.20% V, 0.1% Mo addition. This microstructure shows graphite nodules (black balls), V and Mo carbides precipitates (grey) in a matrix (x 250).



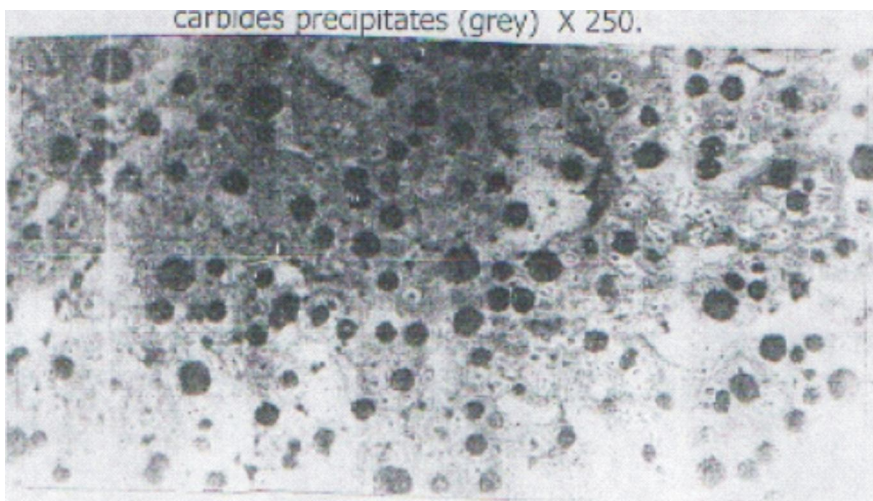
Microstructure B5: The structure of ductile cast iron containing 0.25% V, 0.1% Mo addition. This microstructure shows graphite nodules (black balls), V and Mo carbides precipitates (grey) in a pearlitic matrix (x250).



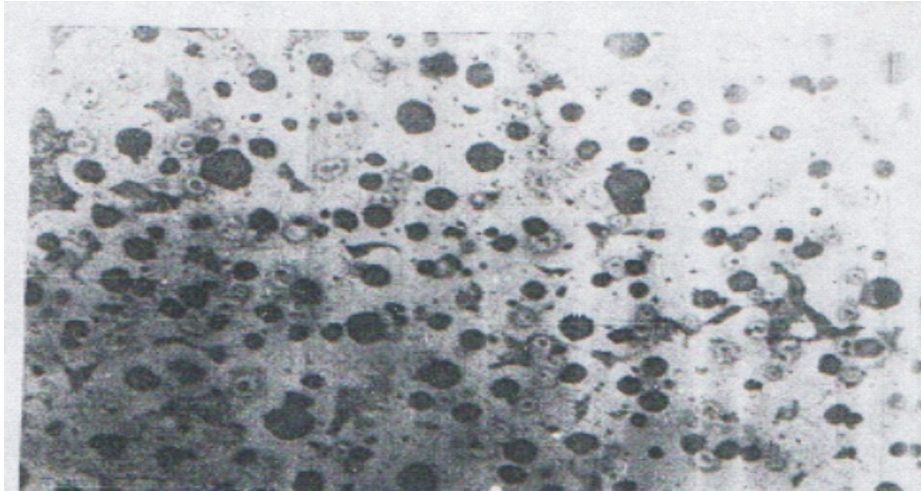
Microstructure B6: The structure of ductile cast iron containing 0.3% V, 0.1 Mo additions. The structure shows graphite nodules (black balls). Surrounding by ferrite rings, few Bull eyes structure, few precipitates of V carbides and few pearlite. (x 250).



Microstructure B7: the structure of ductile cast iron containing 0.1% Mo addition. This microstructure consists of graphite nodules (black balls), surrounded by ferrite rings, (white) pearlite (dark) and M carbides precipitates (grey) (x 250).



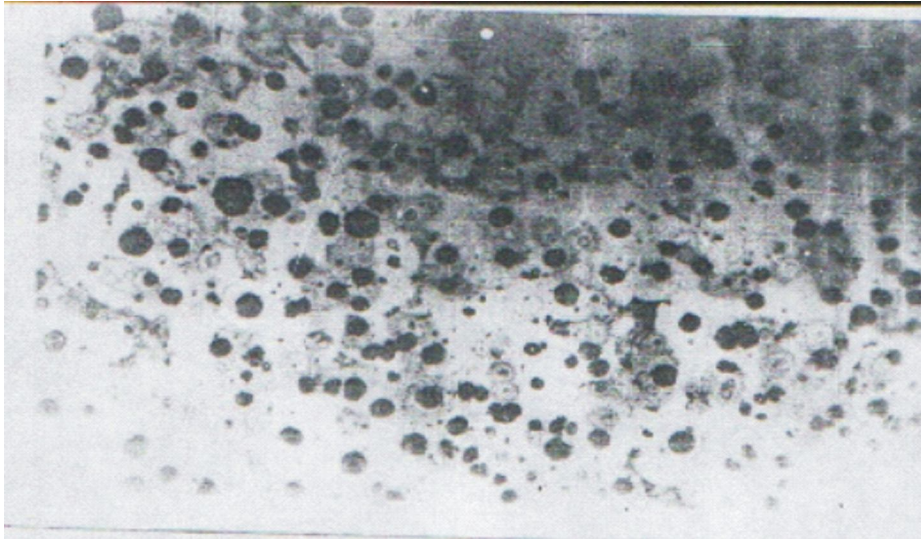
Microstructure B8: The ductile of ductile cast iron containing 0.15% Mo, 0.1% V addition. This microstructure consist of graphite nodules (black balls), completely embedded in fine V and Mo carbides precipitates (grey), and pearlite (dark) (x 250).



Microstructure B9: The structure of ductile cast iron containing 0.20% Mo, 0.1% V additions. This structure shows graphite nodules (black balls), ferrite (white) dominating the matrix; fine precipitates of Mo and V carbides (grey) and pearlite (dark) (x 250).



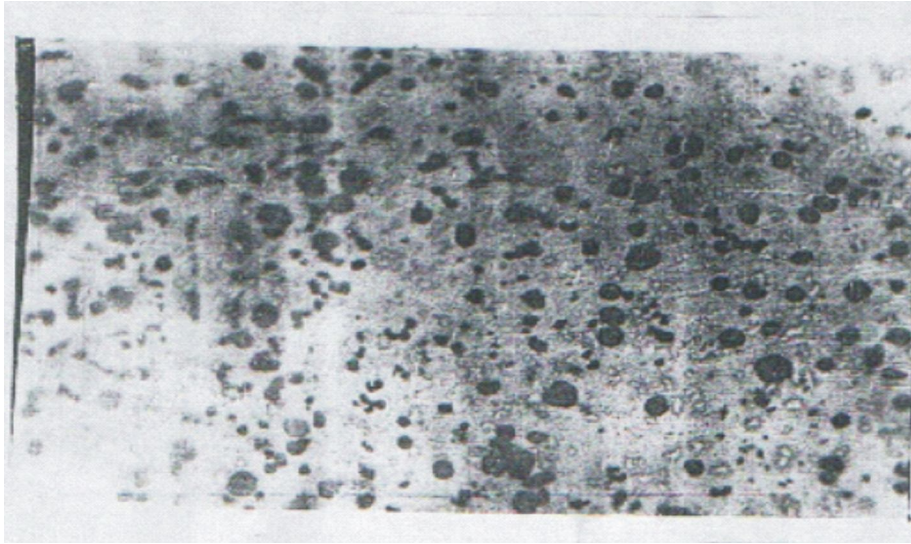
Microstructure B10: The structure of ductile cast iron containing 0.25% Mo, 0.1% V additions. This consists of graphite nodules (black balls) ferrite (white), fine precipitates of Mo and V carbides (grey) and pearlite (dark) (x 250).



Microstructure B11: The structure of ductile cast iron containing 0.30% Mo, 0.1% V addition. This structure consist of graphite nodules, (black balls) in a mixture of ferrite (white), pearlite (dark) matrix and Mo, V carbides precipitates.



Microstructure B12: The structure of plain ductile cast iron that has been normalized. The microstructure consists of graphite nodules in a predominately pearlitic matrix (x 250).



Microstructure B13: The structure of plain ductile cast iron that has been quenched and tempered. The microstructure consists of graphite nodules in a fully martensitic matrix.