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EXPERIMENTAL INVESTIGATION OF EFFECTS OF CHEMICAL VARIABLES ON IRON CASTING

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ABSTRACT

Cast iron is an alloy of iron containing more than 2% carbon as an alloying element. It has almost no ductility and must be formed by casting. Ductile iron structure is developed from the melt of cast iron. The presence of silicon in higher amount promotes the graphitization, inhibiting carbon to form carbides with carbide forming elements present. The carbon forms into spheres when Ce & Mg are added to the melt of iron with very low sulphur content. Due to this special microstructure containing graphite in nodular form ductile iron possesses ductility & toughness superior to that of any cast iron & steel structure resulting in numerous successes in industrial application. Ductile iron castings with 3 and 12 mm thickness with varying chemical composition were cast in furan resin sand moulds to identify the effect of sample thickness on micro structural changes and selected mechanical properties. The effect of melt chemistry and molten metal processing variables (i.e., pre-conditioning of the base iron, inoculation type and practice, and pouring temperature, etc.) on the tensile and impact properties of thin-wall ductile iron castings has been investigated. Comparison of 3 and 12 mm sections within the same casting showed that section size was the main factor influencing tensile properties of ductile irons. While many samples from 3 mm sections showed low elongation values likely caused by a high pearlite content or presence of carbides, many others showed higher elongations and superior strengths well above those required in ASTM A536 grades. At moderate to high elongations, the thin-wall samples were significantly stronger than samples from identical irons of 12 mm section.

A direct comparison between impact values could not be made due to different test specimen sizes, but it is clear that toughness in the two section sizes was roughly equivalent when account was made for the total cross sectional area. The main difference between the Impact properties in the two section sizes lay in the relative in sensitivity of the thin section specimens to either melt chemistry or molten metal processing variables. Of the elements contained in the iron, silicon had the greatest effect on the tensile properties of the thin wall sections. The same increase in silicon content of the thin wall sections had little effect on impact toughness. As expected, any processing variable that led to an increase in nodule count (with a corresponding increase in ferrite content) led to greater ductility, lower strength, and improved toughness. Of the variables studied the greatest effect was found to be from late inoculation, base iron pre-conditioning, and the use of an inoculants containing bismuth and rare earths.

KEYWORDS: graphitization, inoculation, ductility and microstructure

I. INTRODUCTION

Ductile Iron also referred to as nodular iron or spheroidal graphite iron was patented in 1948.After a decade of intensive development work in the 1950s, ductile iron had a phenomenal increase in use as engineering material during 1960s, and the rapid increase in commercial application continues today.

Ductile iron as a technologically useful material has been employed for a score of years. During this period while many investigators have examined its mechanical performance under a wide range of conditions others have attempted to explain its solidification behavior and the many variables which intervene in producing an acceptable product. Yet even at this date we are still at a loss to explain in a fundamental way how an otherwise flake like graphite shape develops in to the spheroidal morphology which gives ductile iron its superior properties.

An unusual combination of properties is obtained in ductile iron because the graphite occurs as spheroids rather than flakes as in grey iron. This mode of solidification is obtained by adding a very small but specific amount of Mg or Ce or both to molten iron of a proper composition. The base iron is severely restricted in the allowable contents of certain minor elements that can interfere with the graphite spheroid formation. The added Mg reacts with S and O in the molten iron and change the way the graphite is formed .Control procedures have been developed to make the processing of ductile iron more effective.

The high carbon and silicon content of ductile iron provide the casting process a few advantages, but the graphite spheroids have only a nominal influence on the mechanical properties of the metal. Ductile iron like malleable iron exhibits a linear stress-strain relation, a considerable range of yield strengths and its name implies ductility. Castings are made in a wide range of sizes with sections that can be either very thin or very thick.

The different grades are produced by controlling the matrix structure around the graphite either simply by casting or by subsequent heat treatment. Only minor compositional differences exist among the regular grades and these adjustments are made to promote the desired matrix microstructures. Alloy additions may be made to ductile iron with a view to control the matrix structure (as cast) in order to provide response to heat treatment. Special analysis of ductile irons and high alloy ductile irons can provide unusual properties for special applications.

Reducing the weight of ductile iron castings i.e., producing thin-section ductile iron castings is an important method for saving energy and material. Let us take an automobile for example a reduction of 100 kg in weight saves 0.5 liter of petrol per 100 km driven. So many metallurgical workers are dedicating themselves to developing and perfecting thin section ductile iron casting technology .Thin section ductile iron castings tend to develop a white or mottled structure and micro porosity during solidification, which can strongly affect the mechanical properties and machinability .It is well known that these defects are significant in the solidification morphology of the castings. In recent years, there has been a clear tendency towards weight reduction on manufacturing mechanical parts in order to reduce costs. In the case of transport industry, this is done also for environmental reasons. When considering thin wall parts, the higher surface to volume ratio makes surface properties essential for part quality and service performance, particularly when such parts are to be used in corrosive environments. Ductile iron has recently been used in thin wall parts. For traditional casting operations, wall thickness reduction implies an increase in the cooling rate and, consequently, microstructural changes. The increase in nucleation rate leads to an increase in the number of graphite nodules, a decrease in grain size and changes in the segregation profile.

Objectives

- To determine the effect of different alloying elements (Carbon, Silicon, manganese copper, Nickel, Cr , Lead, Tin etc.,) on Ductile material.
- To determine the effect of change of different mechanical properties on Ductile iron casting.

II. MATERIALS AND METHODOLOGY

Melting and Casting

Fifteen melts of nodular iron were produced using open ladle treatment method for this study. Charges consisting 50kg pig iron (C=4.17%, Si=1.66%, Mn=0.138%, S=0.024%, P=0.060%), 100kg S.G return (C=3.62%, Si=2.12%, Mn=.19%, S=0.010%, P=0.026%) and 150 kg steel scrap (C=0.038%, Si=0.037%, Mn=0.135%, S=0.005%, P=0.015%) were melted in 250 kg capacity coreless medium frequency induction furnace.

The molten metal was tapped in a preheated laddle containing Ferro silicon magnesium alloy of size 15-25mm (Si=45.50%, Mg=5.85%, Ca=1.08%, Al=0.91%) at the bottom covered with steel scrap. The tapping temperature of molten metal was 1450 C. Commercial argon gas was punched through steel pipe to the melt for proper mixing with addition of 1% Ferro silicon inoculants (3.5 kg) of size 2-6 mm (Si=73.52%, Al=1.06%, P=0.035%, S=0.004%, Ca=0.19%, Ba=2.00%). At this time the sample was taken from the melt for final chemical analysis. The treated iron was poured into furan resin sand molds (Step bar specimen of size as sown in figure 3.1) bonded with epoxy resin and catalyst. The pouring temperature was 1380oC. Similarly other fourteen melts were prepared with varying chemical composition and all melts were properly post inoculated. The chemical compositions of all the raw materials used are obtained from manufacturer's analysis.

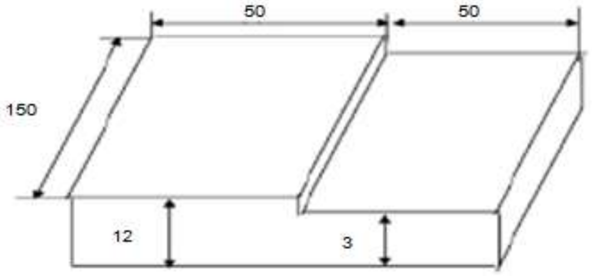


Fig. 2.1 Schematic drawing of step bars, 3 and 12 mm sections, Dimensions are in mm

Test Specimen Preparation

Tensile testing specimens were made from casting obtained from step bars and their tensile strength; yield strength and elongation were measured using Universal Testing Machine (model- UTE 100, max.capacity-1000 KN, Make-Fuel Instruments & engineer's pvt.ltd, Maharahstra, India) as per ASTM standard. Charpy impact test at 20ºC in a Shimadru pendulum of 50J maximum capacity was performed with notched specimen (10x10x55 mm and subsize 2.5x10x55 mm,BSEN 10045-2-1993) cooled in a bath for 5 minutes containing methanol and dry ice for temperature down to 20ºC. The impact values were calculated taking average results of three specimens. The schematic diagrams of the specimens are shown in figure

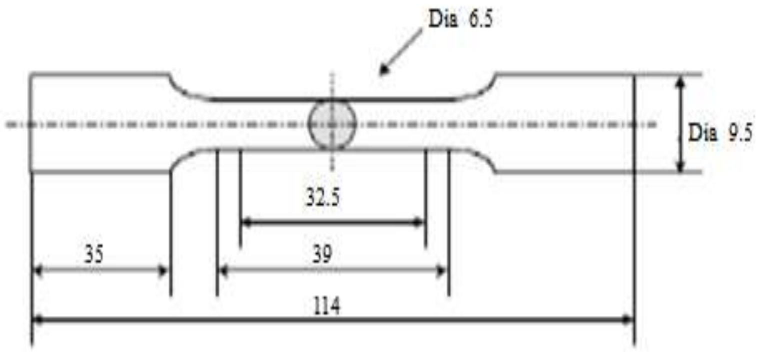


Fig 2.2A Round Tensile Test Specimens (dimensions are in mm)

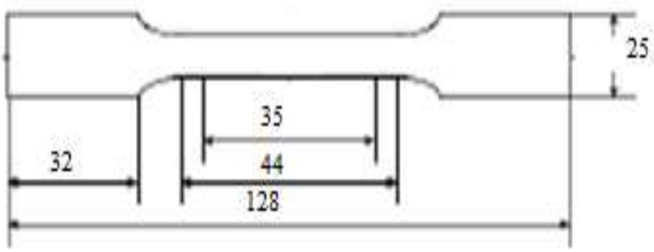


Fig 2.2B Flat Tensile Test Specimens (dimensions are in mm)

Hardness tests were also performed on each sample using Brinell Hardness Tester. Average values of the hardness were obtained based on 5 measurements. A 3000 kg load was applied to specimens with thickness 12 mm and 500 kg for 3 mm sections.

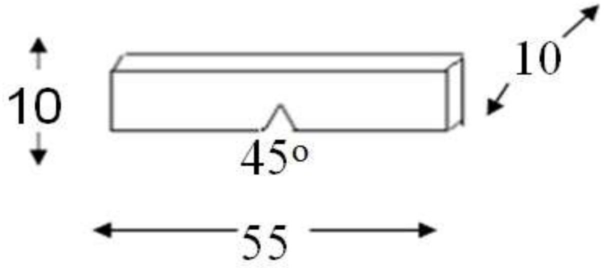


Fig 2.2C V-Notched specimen for charpy impact Test (dimensions are in mm)

Optical Microscopy
The samples for microstructural observation were taken from the centre of the thin-wall casting and mounted with Bakelite. The surfaces of the samples were ground on SiC paper from 220 to 800 grit and polished with 1µm cloth coated with diamond paste. The samples were etched with 2% nital (2% conc. Nitric acid and 98 ml Methanol solution). Then optical micrographs were taken with a 35 mm camera attached to a Leitz microscope.

Analysis with Image Analyzer
The mounted samples after metallographic analysis were put under Image Analyzer (Make-Correct Tokyo, Seiwa optical) to investigate the nodule counts, nodularity and percentage of ferrite and pearlite content in the samples.

Spectrometric Analysis
The final chemistry for each melt was determined using Spectrometer (Spectro lab, M-9 model, Jerman make). The features of the spectrometer (M9-model) are extraordinary from other models. It takes30 seconds for analyzing the composition of each sample and gives accurate percentage of 23 elements present in the sample.

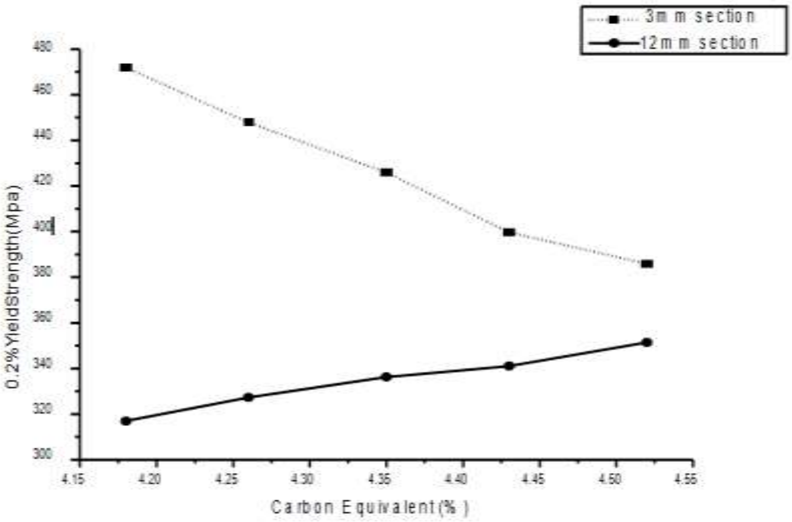
III. RESULTS AND DISCUSSIONS

Effect of Chemical composition on Tensile Properties

Effect of Carbon Equivalent (CE)

Table: 3.1 (Tensile properties of M-1 to M-5)

Melt. No	C.E (%)	0.2% Y.S(Mpa) (3mm sec.)	0.2% Y.S(Mpa) (12mm sec.)	T.S.(Mpa) (3mm sec.)	T.S.(Mpa) (12mm sec.)
M-1	4.18	471.95	316.94	675.22	475.41
M-2	4.26	447.85	327.28	633.88	473.34
M-3	4.35	425.80	336.23	599.43	471.96
M-4	4.43	399.62	341.05	551.20	468.53
M-5	4.52	385.84	351.40	516.75	465.08



3.1a Effect of Carbon equivalent on 0.2% Yield Strength

The result shows both the yield and tensile strength of 3 mm sections decrease significantly with an increase in CE, as a result of increase in ferrite content. On the other hand, 12 mm sections show a slight increase in yield strength with an increase in CE but the tensile strength does not show any effect.

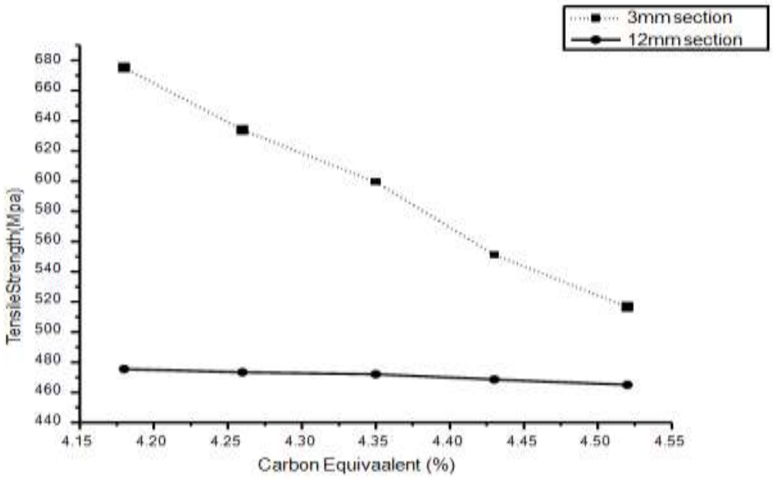


Fig 3.1b Effect of Carbon equivalent on Tensile Strength

Fig. 3.1a and 3.1b show changes in elongation with CE and carbon on 3 and 12 mm sections. The increase in CE shows a small improvement in the elongation of 12mm sections as a result of increase in ferrite but the 3mm sections are not much affected by changes in CE. The elongation of 3 mm sections slightly reduces with an increase in carbon content but the 12 mm sections show improvement in elongation. The increase in carbon content results in a slight increase in the strength of 3 mm sections, whereas the strength of 12 mm sections do not significantly vary despite changes in the carbon content.

Effect of Silicon

Silicon shows the most significant effect on the tensile and yield strength of 3mm sections. This decrease in strength results from the increase in ferrite content/nodule count with an increase in silicon content. The 12 mm sections show a moderate increase in yield strength with an increase in silicon content due to the solid-solution strengthening of the ferrite, whereas the tensile strength is not much affected by change in the silicon level. A strong effect of silicon in increasing the elongation of both 3 and 12 mm sections is shown in Fig.

Table: 3.3 (Physico-chemical properties of M-1 to M-5)

M.No.	Si%	Mg%	Ce%	0.2%YS (Mpa) (3mm section)	0.2% YS(Mpa) (12mm section)	T.S.(Mpa) (3mm section)	T.S(Mpa) (12mm section)	EL (%) (3mm section)	EL (%) (12mm section)
M-1	2.05	0.050	0.004	471.95	316.94	675.22	475.41	5.10	15.0
M-2	2.15	0.045	0.006	447.85	327.28	633.88	473.34	6.00	16.0
M-3	2.25	0.040	0.008	425.80	336.23	599.43	471.96	7.20	17.0
M-4	2.35	0.035	0.010	399.62	341.05	551.20	468.53	7.80	17.5
M-5	2.45	0.030	0.012	385.84	351.40	516.75	465.08	8.50	18.0

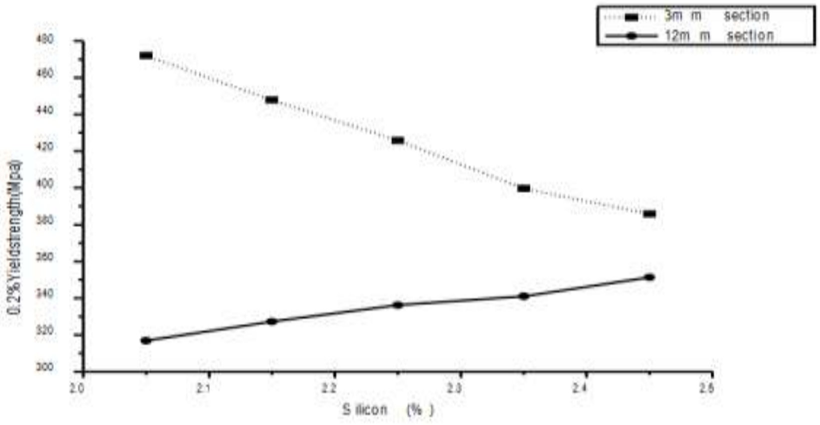


Fig. 3.2a Effect of silicon on yield Strength of 3 & 12mm sections

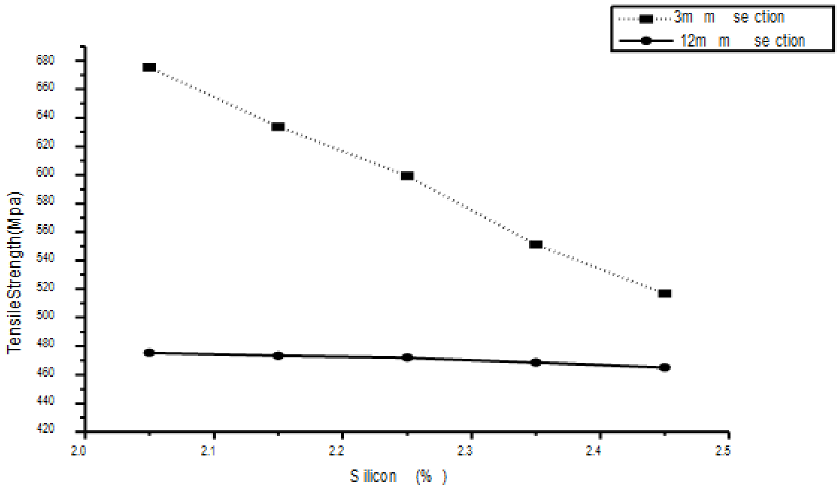


Fig.3.2b Effect of silicon on Tensile Strength of 3 & 12mm sections

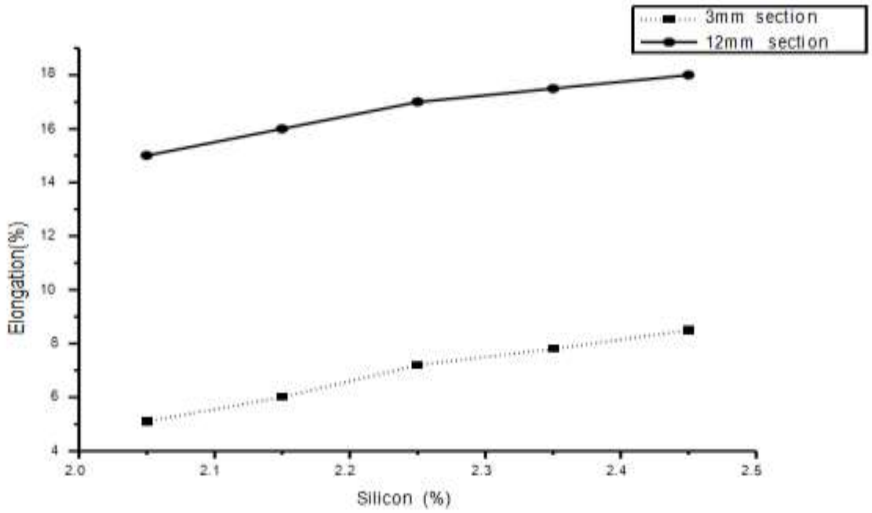


Fig. 3.2c Effect of silicon on elongation of 3 & 12mm sections

Effect of Magnesium

An increase in Mg content is shown to decrease the elongation in both 3 and 12 mm sections (Fig. 12b) as a result of carbide stabilizing effect of Mg in cast iron.

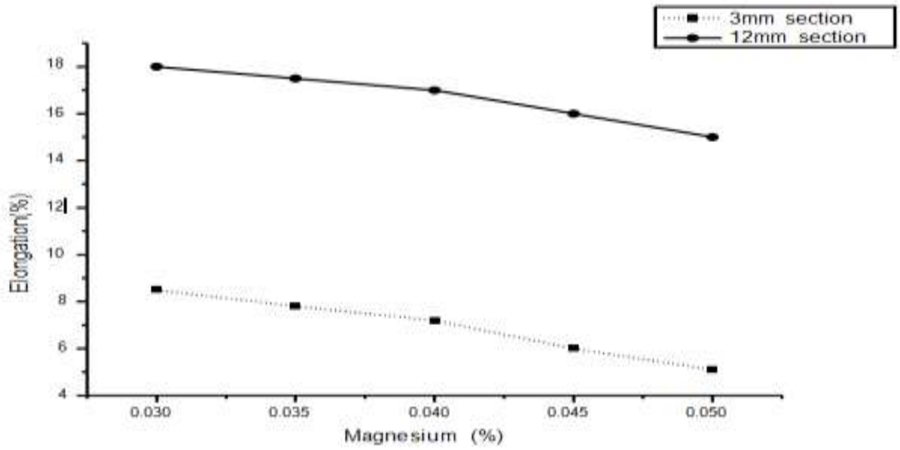


Fig.3.3 Effect of magnesium on elongation of 3 & 12mm sections

Effect of Copper

It is found that copper can have a pearlite promoter role only when combined with a low addition of manganese. An increase in copper content shows a decrease in ductility, but yield strength and tensile strength increases for both 3 and 12 mm sections as a result of pearlite content in the matrix.

Table: 3.4 a (Result of 12mm sections)

Melt No.	C%	Si%	Mn%	S%	P%	Cu%	UTS (Mpa)	0.2%YS (Mpa)	EL%	Hardness (BHN)
M-6	3.62	2.10	0.22	0.011	0.025	0.10	600.2	505	7.12	150
M-7	3.60	2.20	0.19	0.010	0.023	0.20	620.1	535.2	6.82	165
M-8	3.58	2.30	0.20	0.008	0.027	0.30	632.2	566.4	6.34	180
M-9	3.60	2.40	0.21	0.009	0.021	0.40	680.4	584.5	5015	200
M-10	3.57	2.50	0.17	0.011	0.024	0.50	700.2	596.2	4.66	220

Table: 3.4 b (Result of 3mm sections)

Melt No.	C%	Si%	Mn%	S%	P%	Cu%	UTS (Mpa)	0.2%YS (Mpa)	EL%	Hardness (BHN)
M-6	3.62	2.10	0.22	0.011	0.025	0.10	510	425	7.12	120
M-7	3.60	2.20	0.19	0.010	0.023	0.20	530.1	445.2	6.82	135
M-8	3.58	2.30	0.20	0.008	0.027	0.30	550.2	466.4	6.34	150
M-9	3.60	2.40	0.21	0.009	0.021	0.40	565.4	484.5	5.15	165
M-10	3.57	2.50	0.17	0.011	0.024	0.50	580.2	500.2	4.66	180

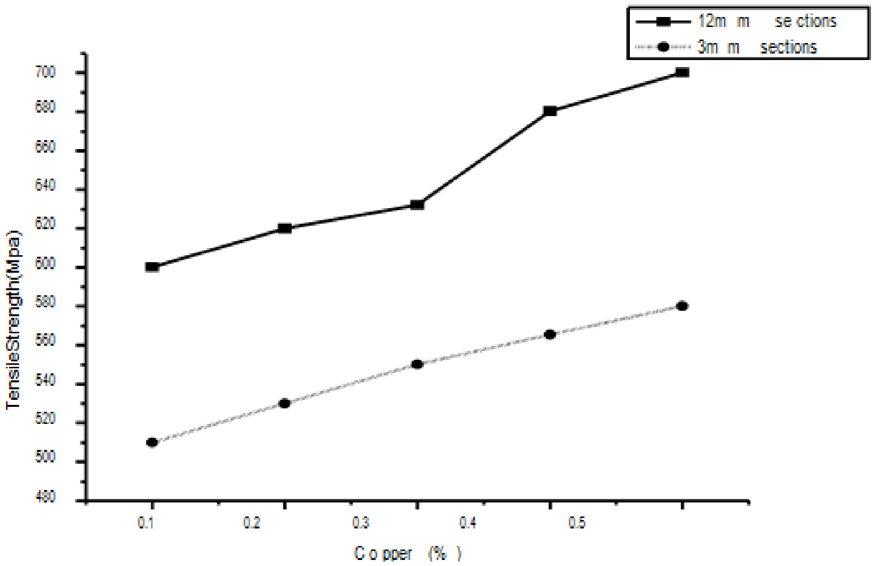


Fig.3.4 Effect of copper on Tensile strength of 3 & 12mm sections

Effect of Chemical composition on Impact Properties

The V-Notched charpy impact energies of all melts were determined as described in the experimental procedure. The effect of chemical composition on impact properties was studied and described below.

Effect of Carbon Equivalent (CE)

The impact energies of 12 mm sections decrease with an increase in CE, whereas the 3 mm sections do not show much effect.

Table: 3.5 (Avg. impact result of 3 & 12mm sections)

Melt no.	CE (%)	C (%)	Avg.impact energy(J),12mm sections	Avg.impact energy(J),3mm sections
M-1	4.18	3.50	14.2	8.30
M-2	4.26	3.55	13.5	8.40
M-3	4.35	3.60	13.2	8.50
M-4	4.43	3.65	12.8	8.60
M-5	4.52	3.70	12.5	8.80

Effect of Silicon

The effect of silicon on V-notched charpy impact energies for 3 & 12 mm sections was studied from melt no M-6 to M-10 as shown in figure 3.5 and the data given in table 3.6. Silicon shows a strong effect on the impact energies of 12 mm sections, while the 3 mm sections show a much smaller effect.

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Table: 3.6 (Avg. impact energy of M-6 to M-10)

Melt no	Si (%)	Cu (%)	Avg.impact energy(J),12mm sections	Avg.impact energy(J),3mm sections
M-6	2.10	0.10	9.20	5.20
M-7	2.20	0.20	7.30	5.00
M-8	2.30	0.30	6.40	4.90
M-9	2.40	0.40	5.20	4.80
M-10	2.50	0.50	4.50	4.60

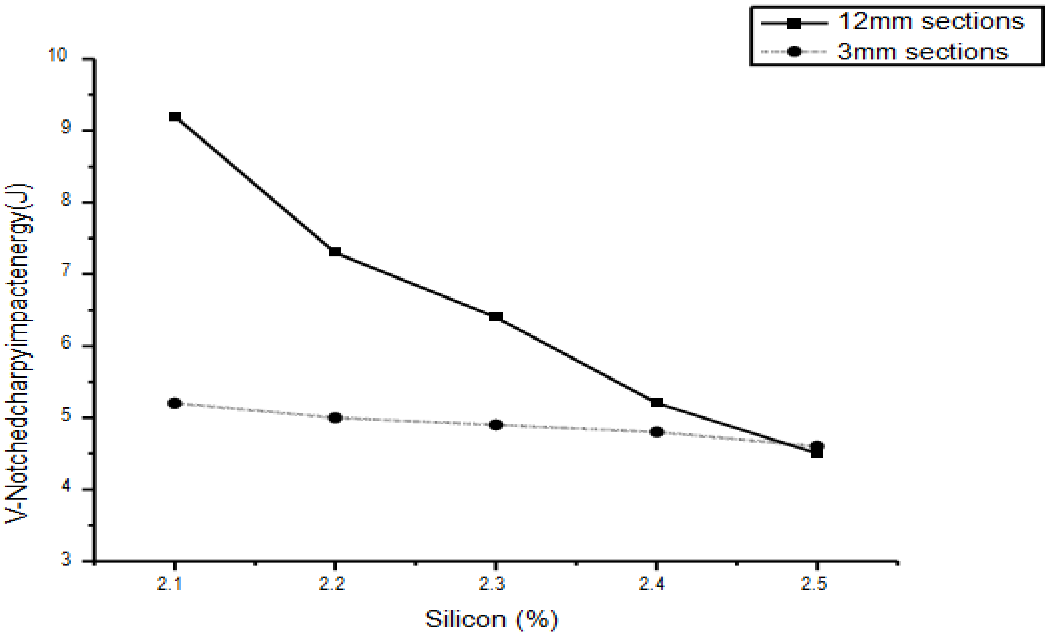

Fig.3.5 Effect of silicon on impact energy of 3 & 12mm sections

Effect of Copper

The effect of copper on V-notched charpy impact energies for 3 and 12mm sections was studied for the melt no M-2, M-6 and M-7.

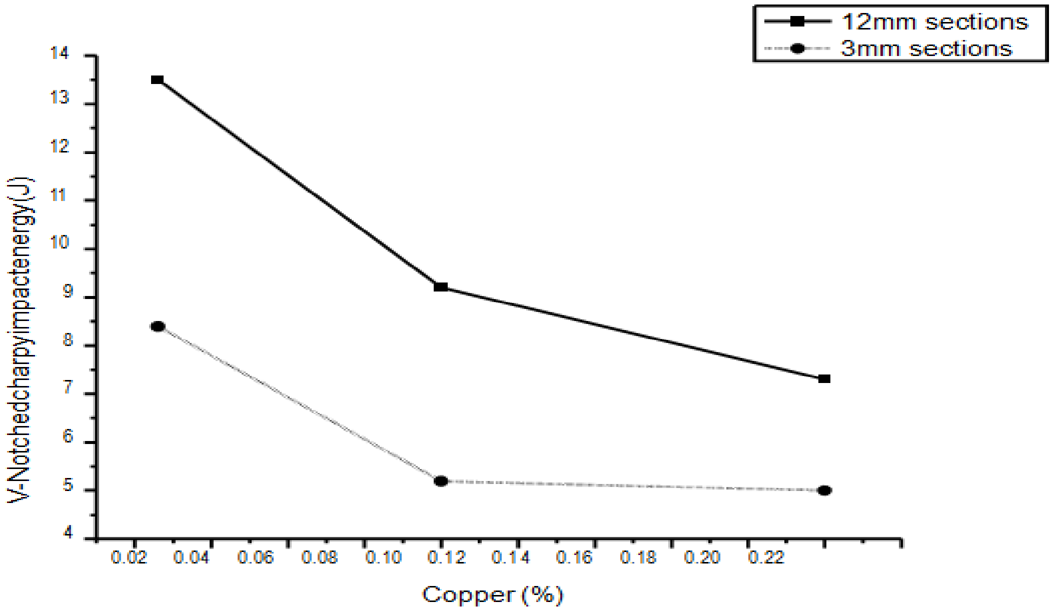

Fig. 3.6 Effect of copper on impact energy of 3 & 12mm sections

The influence of copper is complex and depends upon whether the iron contains subversive elements such as titanium , in which case even as little as 1 percent copper can cause the formation of substantial amounts of flake graphite.

An increase in the cerium content produces an improvement in the impact properties of both the 3 and 12 mm sections. This might be as a result of an increase in the nodule count with the addition of cerium, which promotes ferrite. The increase in Mg content results in a slight decrease in the impact values of 12 mm sections but the 3 mm sections are not much affected by changes in Mg. The small variations in Mn and S content have no effect on the impact properties. On the other hand, the presences of certain residual elements such as Cr and Al, even in very small ranges, show a significant effect on the impact properties of 12 mm sections but no effect in 3 mm sections.

IV. CONCLUSION

Ductile iron is characterized by having all of its graphite in the form of microscopic spheroids. Although this graphite constitutes about 10% by volume of ductile iron, its compact spherical shape minimizes the effect on mechanical properties. The graphite in commercially produced ductile iron is not always in perfect spheres. It can occur in a somewhat irregular form, but if it is still chunky as Type II in ASTM Standard A247, the properties of the iron will be similar to cast iron with spheroida graphite. Of course, further degradation can influence mechanical properties. The shape of the graphite is established when the metal solidifies, and it cannot be changed in any way except by remelting the metal.

All the mechanical properties of the present investigation are compared with quality base line of ASTM A536 specifications. The conclusions could be drawn from the analysis. The increase in nodule count from 600 to 1500 Nod/mm^2 promotes higher metal loss. Metal loss increases with strain hardening for all the experimental conditions tested.

Section size is the main factor influencing tensile properties of ductile irons. The main difference between the impact properties in the two section sizes lies in the relative intensity of the thin section specimen to either melt chemistry or molten metal processing variables. Silicon has the greatest effect on the tensile properties of the thin wall sections but has little effect on impact toughness. Production of nodular graphite structures by the process described in this experiment may represents a good understanding in the field of the metallurgy of cast iron. Copper has the greatest effect on the tensile properties of thin wall sections but has little effect on impact properties as observed in the experiment. Introduction of copper in high amount produces adverse effect on the mechanical properties, but by using copper-magnesium-cerium alloys this danger will be avoided. Processing variables (pre-conditioning of base iron, inoculation practice and pouring temperature) lead to an increase in nodule count which results in greater ductility, lower strength and improved toughness. The inoculation technique is of indispensable for commercial utility.

Addition of small amount of cerium has produced a marked improvement in the tensile strength of both the sections due to replacement of a mixed flake and nodular graphite structure by a completely nodular graphite structure. Graphite nodules are generally finer in the thinnest sections. Number of graphite nodules increases as the castings thickness decreases. It exceeds 2000 nodules per mm^2 in the thinnest sections. Nodularity is generally above 80% in both the sections i.e. 3mm sections and 12mm sections. Presence of trace elements like copper, arsenic, antimony, bismuth, lead, indium, tin and thallium promoted the formation of pearlite in the as cast structure as studied from melt chemistry and microstructure analysis. The elongation is improved with the addition of rare earth content up to 0.03% in ductile iron castings however the nodule count decreases with increase in section size. In order to achieve the desired physical properties it is recommended to have the chemical composition as follows.

In fact, reduction in the thickness of the castings leads to an increase in strength but a decrease in ductility as the nodularity decreases with increasing solidification time. The nodularity of graphite nodules is improved due to the addition of RE (rare earth elements) and the amount of ferrite was observed to depend on RE and sample thickness. The addition of rare earths leads to a higher amount of ferrite than that of the specimens without RE.

The ferrite content was found to be the lowest for the 3 mm specimen with 0.02% RE. Microstructure of ductile iron step bar castings with section thickness of 3 mm and 12 mm were characterized quantitatively. The observations can be summarized as

(a) Pearlitic content increases with decreasing thickness of the castings.
(b) Number of graphite nodules increases as the casting thickness decreases. It exceeds 2000 Nod/mm^2 in the thinnest sections.
(c) Graphite nodules are generally finer in the thinnest sections. The late inoculation process introduced in the present investigation produces nucleation centers for nodular graphite precipitation more effectively than the in stream inoculation process.

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