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# The Production Technology of a Modern Material for Heavy Automotive Vehicles - A Compacted Graphite Iron (C.G.I.)

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## Introduction

The invention of Compacted Graphite Iron and documentation of Compacted Graphite Iron (C.G.I.) were made during pioneering research on production techniques in the late 1940s. They found that when the residual magnesium or cerium content was insufficient to stabilize a fully spheroidal graphite then the intermediate form of graphite is formed which is Compacted Graphite or vermicular appeared in the microstructure. It was up to 1960s that CGI began to be recognized as a modern material combining much of the strength and stiffness of ductile iron with the thermal conductivity and castability of grey cast iron.

*Today the result is that where reduced weight and improved performance particularly for automobile cylinder blocks and heads; where mechanical and physical properties of CGI can contribute to meeting the conflicting requirements of weight reduction, improved performance, reduced emissions, recyclability and cost reduction there is tremendous demand for Compacted Graphite Iron to substitute grey iron or ductile iron castings.*

The Compacted Graphite Iron (C.G.I.) castings are not only used for only heavy vehicles but they are being used for the engines of passenger vehicles in United Kingdom as well as all European countries on regular basis for last many years and Sintercast Ltd. will promote these castings on similar manner in all other countries including India. Only thing Indian foundry-men should come forward with positive and keen interest to use this unparallel material.

Now the Compacted Graphite Iron (C. G. I) castings are the twenty first Centaury material for the engine blocks of heavy vehicles. At present its Production in India has been successfully done by very few foundries. Just like Austempered Ductile Iron ( ADI ) for producing Compacted Graphite
Iron casting it is mandatory to have strict discipline in all stages of productions particularly in Magnesium Treatment and post inoculation production particularly in Magnesium Treatment and post inoculation techniques.

**The Global Market for Compacted Graphite Iron Castings:**
The need for C.G.I. process increases with increasing production volumes, geometric complexity and narrowness of the microstructure specifications. The main applications are:

**Automobile and Marine Engines –Blocks, Heads, Bedplates; Exhaust Manifolds, Hydraulic Housings & Brackets, Flywheels, Bearing Caps, and Ingot Moulds; Heavy Castings, Components of the Passenger Vehicles also are Important.**

Initially the use of this process was limited for high volume production due to the discipline in all stages of production of CGI are required just like Ductile Iron process. But now introduction of novel control technologies have resolved the foundry production issue.

**The Mechanical Properties of Compacted Graphite Iron:**
Refer Table 1 for ready reference with respect to microstructure in matrix.

Table No. 1 - The Mechanical Properties of Compacted Graphite Iron:

| GRADE | Min. U.T.S. Mps. | Min.0.2 % Y.S. MPs. | % Elongation | Typle Hardness B.H.N. 10/3000 |
|---|---|---|---|---|
| 250 | 250 | 175 | 3.0 | 179 max. |
| 300 | 300 | 210 | 1.5 | 143-207 |
| 350 | 350 | 245 | 1.0 | 163-229 |
| 400 | 400 | 280 | 1.0 | 197-255 |
| 450 | 450 | 315 | 1.0 | 207-269 |

**Factors affecting the Mechanical Properties of Compacted Graphite Iron:**

A) Microstructure:
B) Composition:
C) Section Thickness:
D) Magnesium Treatment:

E) Inoculation after Magnesium Treatment:
F) Foundry Characteristics:
G) Machinability of C.G.I.:
H) Special Applications:
I) Future of C.G.I.

Here some of the important factors will be discussed and other factors will come on Practical Tips for the various steps of production of C.G.I.

Table No. 2 - A) Effect of Microstructure of C.G.I. on Mechanical Properties.

| Properties | Ferrite | Perlite |
|---|---|---|
| **Tensile Properties –** | | |
| Ultimate Strength ( MPa) | >300 | >400 |
| 0.2 % Yield Strength ( MPa) | >200 | >300 |
| Elastic Modulus (Gpa) | 140-155 | 145-160 |
| % Elongation | 2.5 | 0.5-2.0 |
| Poisons Ratio | 0.25 | 0.26 |
| **Compression Properties –** | | |
| Strength limit (MPa) | >500 | >1000 |
| 0.2 % Yield Strength (MPa) | >290 | >415 |
| Elastic Modulus (GPa) | 140-155 | 145-160 |
| Brinnel Hardness (10/3000) | 150-190 | 190-260 |
| **Fatigue Properties –** | | |
| Rotating bending limit.Un notched | >175 | > 200 |
| (MPa) | 0.55 | 4.5 |
| Esurient Ratio | 1.3 –1.60 | 1.4 – 1.7 |
| Fatigue Strength reduction factor | > 110 | >175 |
| Tension-Compression limit (MPa) | > 150 | > 200 |
| Three Point Bending limit (MPa) | > 140 | >200 |
| Fully reversed torsion limit (MPa | | |
| **Toughness Values –** | 3.5 | 4.5 |
| Notched Charpy Impact (J) | 15-20 | 7- 10 |
| Unnotched Charpy Impact (J) | >600 | >700 |
| Bending Strength (MPa) | >275 | > 325 |
| Shear Strength (MPa) | | |

## Microstructures of Compacted Graphite –

## Definition of Compacted Graphite Iron Microstructure –

- Optical Metallography exhibits graphite that is similar to type IV ASTM A 247 graphite.

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- Compacted graphite appears in clusters that are **interconnected** within the eutectic cells. The graphite appears as thicker, shorter flake graphite.

- An acceptable CG iron is one in which Min 80% of the graphite is compacted graphite, **maximum of 20% spheroidal graphite**

- **No flake graphite present in microstructure.**

**Comparison of Grey Cast Iron, Ductile Iron & Compacted Graphite Iron**:

Figure 1. Microstructures of Grey Cast Iron, Ductile Iron and Compacted Graphite Iron- (Mark the difference in un-etched condition the shapes of graphite)

(A) Grey Cast Iron (B) Ductile Iron (C) Compacted Graphite

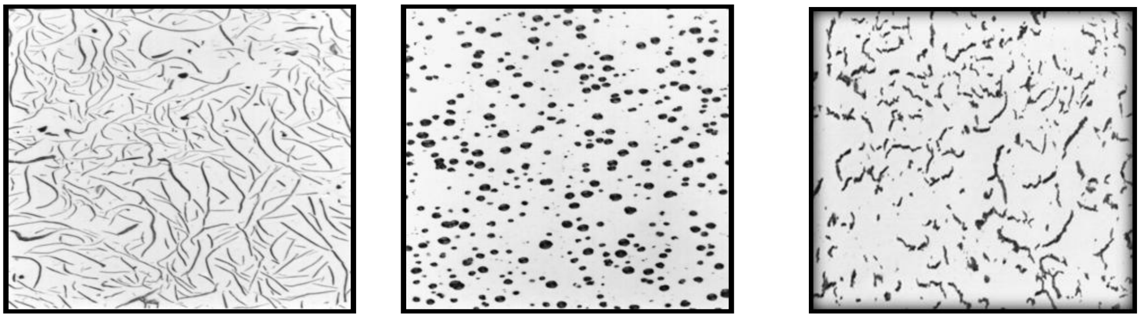
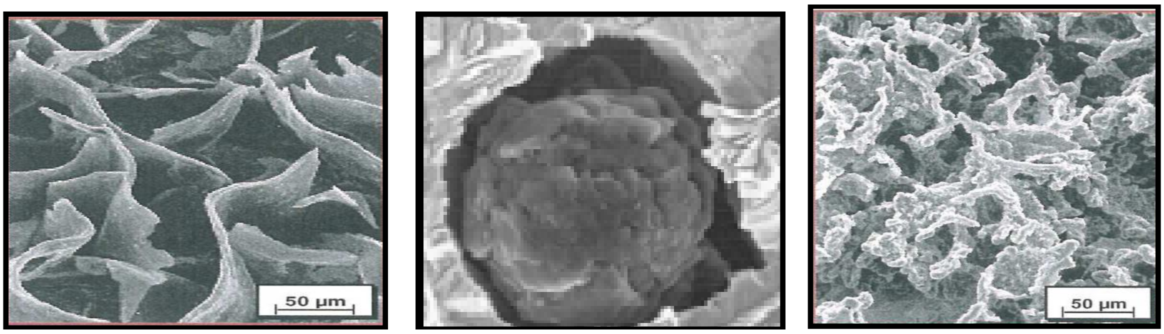


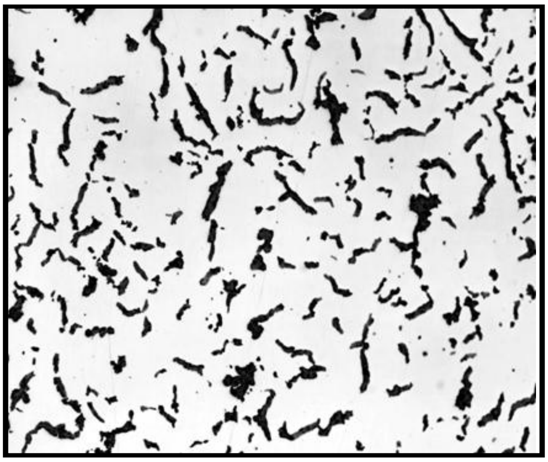
Figure -2. SEM Microphotographs of Grey Iron, Ductile Iron & Compacted Graphite Iron.

Grey Cast Iron Ductile Iron Compacted Graphite Iron

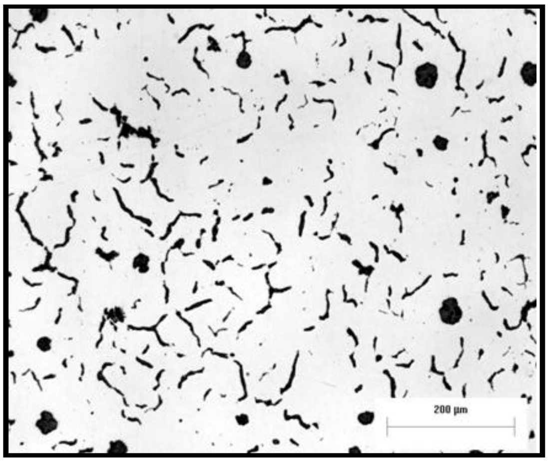



The figure - 2 shows a deep etched SEM micrograph of the three dimensional compacted graphite morphology indicating interconnected "coral-like" graphite cluster. As compared to flake graphite these are shorter, thicker and have rounded edges and roughened surfaces & this roughened surface improves adhesion to the ferritic matrix and minimises both initiation and propagation of cracks which results in improved tensile, fatigue strength and elastic modulus which has been indicated.

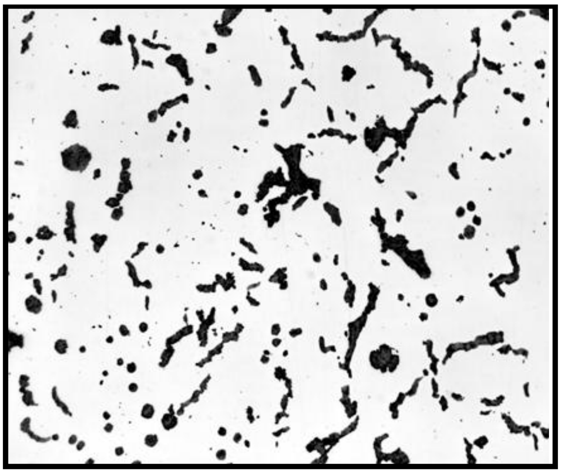
Figure -3. Proportions of Nodularity in the Microstructure of Compacted Graphite Iron.



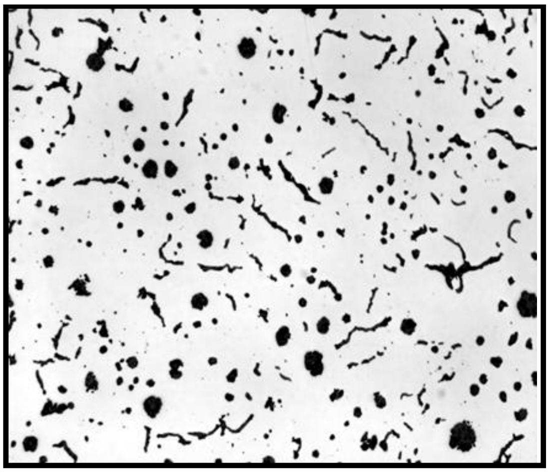
Nodules 5 %




Nodules 15 %



Nodules 30 %



Nodules 50 %

## B) Composition of Compacted Graphite Iron:

Table No. 3 - Chemical composition and Microstructural data for some heats:

| No | C | Si | Mn | S | Mg | Cu | Sn | Cr | Al | P | P* % | N ** % |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 3.63 | 2.49 | 0.42 | 0.014 | 0.007 | 0.42 | 0.039 | 0.02 | 0.008 | 0.010 | 25 | 4 |
| 2 | 3.54 | 2.49 | 0.41 | 0.010 | 0.007 | 0.40 | 0.040 | 0.02 | 0.003 | 0.011 | 45 | 4 |
| 3 | 3.54 | 2.50 | 0.41 | 0.012 | 0.010 | 0.41 | 0.040 | 0.02 | 0.003 | 0.011 | 50 | 8 |
| 4 | 3.61 | 2.49 | 0.40 | 0.014 | 0.008 | 0.45 | 0.053 | 0.03 | 0.004 | 0.011 | 75 | 7 |
| 5 | 3.59 | 2.48 | 0.39 | 0.013 | 0.011 | 0.71 | 0.094 | 0.03 | 0.007 | 0.011 | 94 | 6 |
| 6 | 3.60 | 2.45 | 0.40 | 0.014 | 0.008 | 0.45 | 0.051 | 0.03 | 0.004 | 0.010 | 86 | -3 |
| 7 | 3.57 | 2.48 | 0.39 | 0.014 | 0.006 | 0.72 | 0.094 | 0.03 | 0.008 | 0.010 | 93 | -2 |
| 8 | 3.58 | 2.48 | 0.39 | 0.016 | 0.010 | 0.71 | 0.094 | 0.03 | 0.008 | 0.010 | 99 | 0 |
| 9 | 3.57 | 2.50 | 0.40 | 0.011 | 0.023 | 0.41 | 0.039 | 0.03 | 0.003 | 0.011 | 87 | 33 |
| 10 | 3.50 | 2.47 | 0.41 | 0.010 | 0.027 | 0.44 | 0.052 | 0.02 | 0.003 | 0.011 | 90 | 67 |
| 11 | 3.58 | 2.50 | 0.39 | 0.012 | 0.030 | 0.72 | 0.095 | 0.03 | 0.007 | 0.011 | 90 | 80 |

*P means Perlite - ** means Nodularity.

In the Table No.-3 for heats 6 and 7 the nodularity has been shown as negative it means that there are graphite flakes present and therefore the nodularity is termed as negative.

Figure 4. Compacted graphite microstructure contains flake graphite patches and so assigned value of -2 % Nodular.

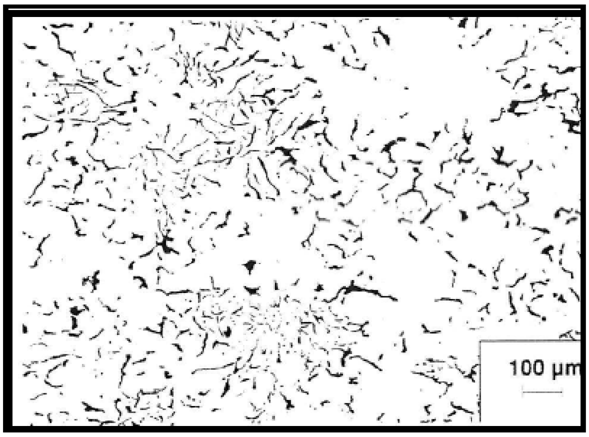
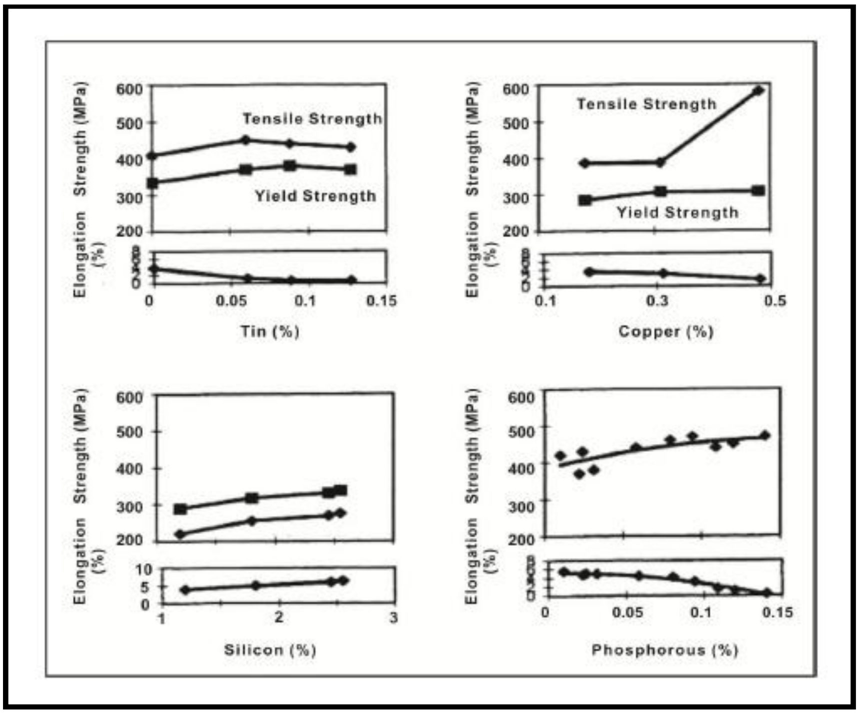


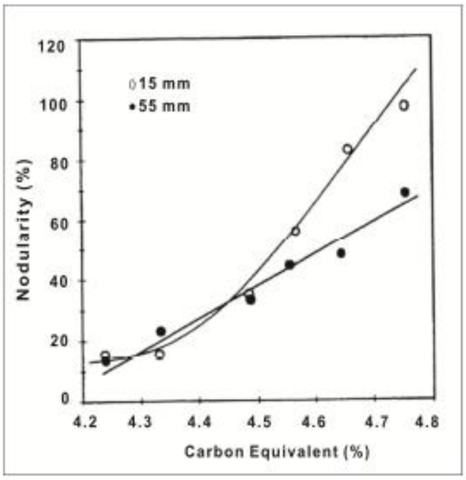

Figure - 5 Effect of Tin, Copper, Silicon and Phosphorous on Mechanical Properties of Compacted Graphite Iron.

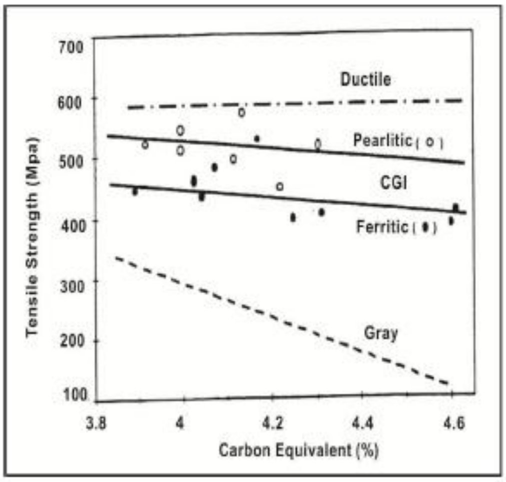



The Figure 5 Indicates the effect of Copper, Silicon, Tin and Phosphorous content on the Tensile Strength, Yield Strength and ductility of C.G.Iron. So the control in melting is primary of importance to control Mechanical Properties.

Figure - 6 Carbon Equivalent of CGI. V/s Nodularity %.

Figure - 7 Carbon Equivalent V/s T. Strength of C.G.I.

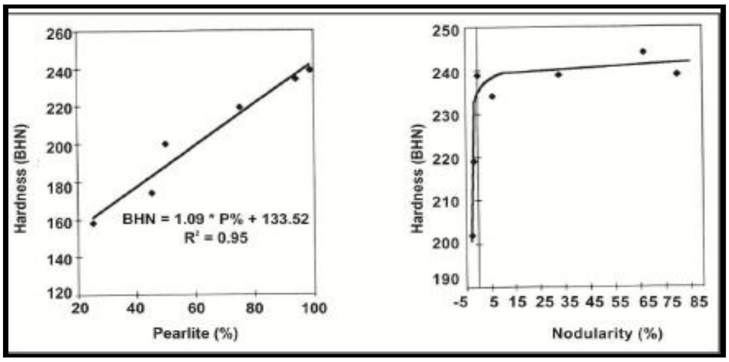



In the composition two main elements are Carbon and Silicon and the effect of Carbon Equivalent on Nodularity % and the microstructure control the Tensile Strength are related.

**C) Section Thickness of Castings:**

Figure - 8 Graph on Left shows relation of hardness in B.H.N. with Perlite % and Graph on Right relates hardness in B.H.N. with modularity values of Compacted Graphite Iron.




At a fixed 85 to 100 % Perlite % the B.H.N. is effectively constant with 90 % Nodularity. In curve two it can be seen that nodularity of 2.5 % also gives hardness of 235 B.H.N. in C.G.I. ( Refer figure 8 Left and Right Curves)

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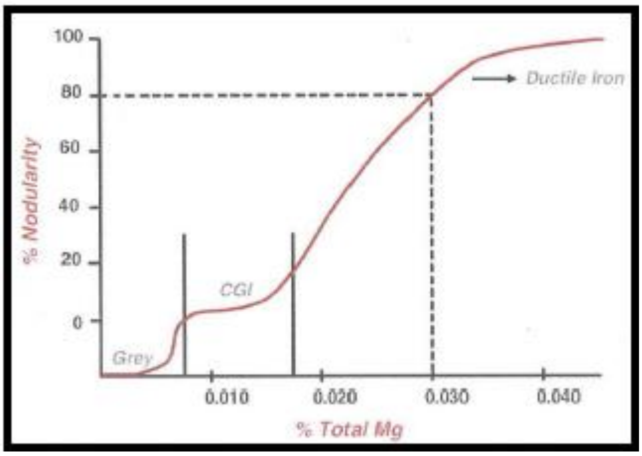
**D) Magnesium Treatment after Melting:**

**Magnesium Treatment:** The magnesium treatments are divided in two stages (A) Melting Process and (B) Magnesium Treatment.

(A) The effect of all important elements are discussed above. The Magnesium Treatment is given after once the composition is achieved as per requirement.

Ferrosilicon Magnesium with Magnesium 5 % Titanium 9 % Calcium 1 % Ceriumo.o2 to o.05 % and balance Silicon & Iron is used to control the Nodularity as low as possible to obtain C.G.I.

Figure - 9 The classification of Grey, Compacted Graphite and Ductile Irons based of the % of residual magnesium in the metal.




The stable magnesium range for compacted graphite growth is separated by an abrupt transition to flake graphite and gradual transition to nodular graphite. It can be observed from the Table No.- 3 that the % of residual magnesium is in the range of 0.007 to 0.010 and higher than this increases the nodularity of about 80 % with residual magnesium of 0.03 %.

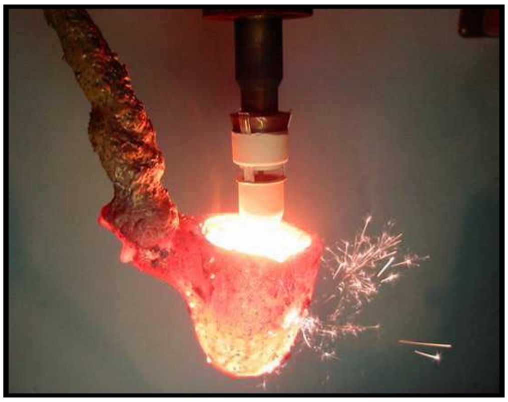
**( B ) The Sintercast Process**

In the sintercast process magnesium alone is added and the addition is controlled by novel modern technology by using computer controlled residual Magnesium level. Initially the iron is deliberately undertreated and its "Composition" is determined by a novel thermal analysis procedure (Figure 10) The condition is then adjusted to give consistent well compacted graphite by wire feed treatment which provides the necessary further magnesium and inoculant additions. The special thermal analysis process uses a specially designed sampling cup ( Figure 11 ) two thermocouples to assess the oxygen and sulphur activity of the iron. This analysis is carried out on line in about 3 minutes with real time control of subsequent wire feed completing treatment prior to pouring in moulds.

The thermal analysis is of very importance as it can indicate the type of graphite will be formed and for the production of compacted graphite iron the modularity must be as low as possible by reducing the ultimate residual magnesium in the metal during inoculation process. This is the last but very is of significance as far as the formation of compacted graphite over 90 to 95 % to produce quality C.G.I. The type of inoculant used is also of very importance to achieve fully compacted graphite.

Figure -10. Thermal Analysis Procedure of CGI.

Figure – 11. Specially designed sampling cup for cooling curve.

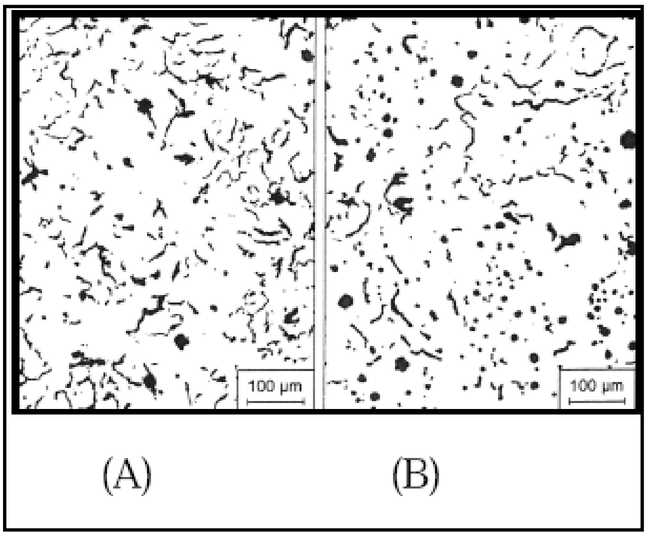


D) **Post inoculation:**

In case of production of compacted graphite iron is more critical than in the production of S. G. Iron/ Ductile Iron. Normally the inoculants used are almost of same composition .However the amount used is of at most important because the small variation in quantity of inoculant will convert compacted graphite into spheroidal graphite. The post inoculation treatment is as important as magnesium treatment stage because the composition of the inoculant controls the ultimate silicon content of metal.

The effect of the other elements from inoculant will be also harmful to improve nodularity of the C.G.I. which has to be controlled precisely during the last stage of production of compacted graphite iron castings as per the specification. The amounts of the inoculant used definitely affect the microstructure of C.G.I.

Figure -12. Effect of Post Inoculation on the Nodularity of a Compacted Graphite iron.




A CGI cast 25 mm diameter bar (A) shows after base treatment (3 %) Nodularity and (B) after 0.075 % post inoculation (21 % Nodularity.)

**Mechanism of Formation of Compacted Graphite:**

The graphite particles in compacted graphite iron (C.G.I) appear as individual worm shaped or vermicular particles. The particles are elongated and randomly oriented as in grey iron because of absence of surface tension of magnesium oxide vapour pressure as in case of graphitisation of nodules in S. G. Iron. However, they are shorter and thicker, and have rounded edges due to the effect of residual magnesium in the metal. The worm shaped graphite when viewed in two dimensions deep etched Scanning Electron Microscope (SEM) micrographs show that the individual worms are connected to their nearest neighbours within the eutectic cells. This complex coral like graphite marphology, togather with the rounded edges and irregular bumpy surfaces, results in strong adhesion between the graphite and the iron matrix. The compacted graphite morphology inhibits crack initiation and growth and is the source of the improved mechanical properties relative to grey iron.

**CASE STUDY 1**

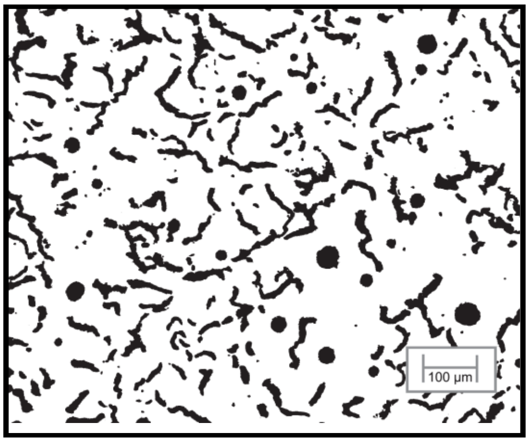
**(By courtesy of Dr. Steve Dawson, President & CEO-SINTERCAST LTD. U,K. )**

Table No. - 5. Chemical Composition of Compacted Graphite Iron

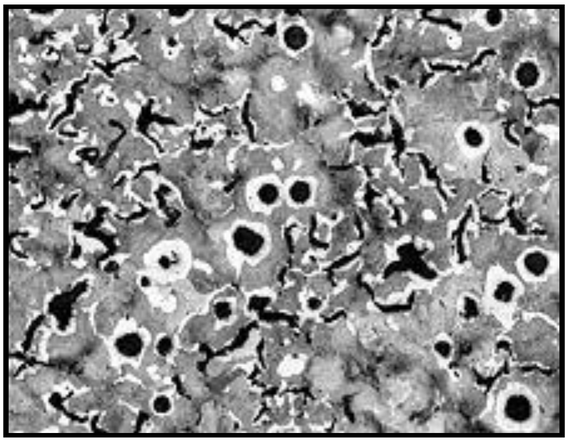
| Matrix Structure | Chemical Analysis in ( % ) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | C | Si | CE | Mn | S | Mg | Ce | Cu | Sn |
| 70 % Pearlite | 3.6-3.8 | 2.1-2.5 | 4.4-4.7 | 0.2-0.4 | 0.005-0.022 | 0.006-0.0140. | 0.01-0.03 | 0.3-0.6 | 0.03-0.05 |
| 100 % Pearlite | 3.6-3.8 | 2.1-2.5 | 4.4-4.7 | 0.2-0.4 | 0.005-0.022 | 0.006-0.014 | 0.01-0.03 | 0.6-0.9 | 0.08-0.10 |

**Microstructure of Compacted Graphite Iron**

Figure -13. Effect of Post Inoculation on the Nodularity of a compacted graphite iron. (a)Unetched Condition (b) In etched condition




Un-Etched (a) 100 X
20 % Nodularity.



Nital Etched (b) 100 X
C.G.I. with more than 90 % Perlite.

Table - 6. Mechanical and Physical Properties of 10 % Nodularity C.G.I

| Properties | Test Method | 70 % Pearlite | 100 % Pearli |
|---|---|---|---|
| UltimateTensile Strength MPa . | ASTME 8 M ($25^0$C)* | 420 | 450 |
| 0.2 % Yield Strength MPa | ASTME 8M ($25^0$C)* | 315 | 370 |
| Elongation % | ASTME 8M ($25^0$C )* | 1.5 | 1.0 |
| Thermal ConductivityW/m C | ASTME 1225 | 37 | 36 |
| 0.2 % Compressive Yield ( MPa ) | ASTME 9 ( Medium length ) | 400 | 430 |
| Brinell Hardness B.H.N. | 10 mm diameter Ball 3000 Kg Load | 183 - 235 | 207 - 255 |

*These properties are also determined at 100 0 C and 300 0 C

**Process control parameters and production tips for magnesium treatment to control residual magnesium after magnesium treatment:**

**Magnesium Treatment:** The effective magnesium treatment will give required compacted graphite by keeping nodularity to as minimum as possible. This control on residual magnesium is not only important for avoid more nodule formation but also to avoid formation of flake graphite which will affect the mechanical properties of C. G. I. The residual Magnesium is to be controlled to achieve complete microstructure free form nodularity & no carbides are present.

Figure- 14. The curve showing relation of Magnesium as Noduliser & Ti used.

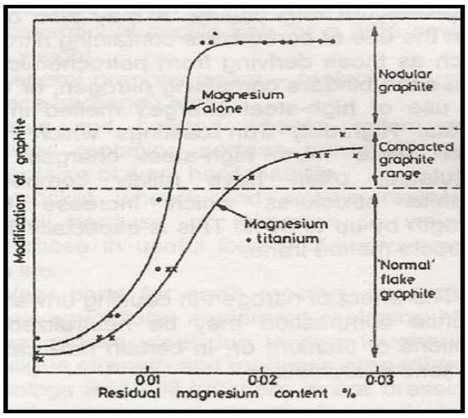
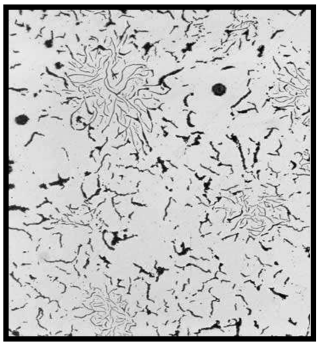



Figure - 15. (A) And (B) show effect of addition of 0.007 % active Magnesium is sufficient to convert a flake patch microstructure into a high Quality CGI microstructure.

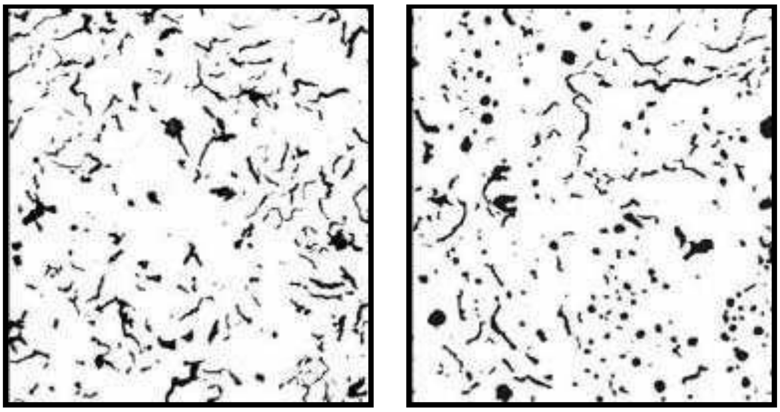
Figure -15. (A) Figure - 15 (B)



**(c) Post inoculation :** High inoculation levels provides more nuclei favours the formation of nodular graphite. Sensitivity to inoculation is illustrated in figure -16 (a ) and ( b ) which shows that the addition of just 80 grams of inoculant to one ton ladle can change the nodularity from 3 % to 21 % nodularity in 25 mm diameter test bar casting.

Figure - 16(a) Nodularity 3 % only. Figure - 16 (b) Nodularity increased to 21 %.

Figure - 16 (a)                Figure - 16 (b)



Nodularity 3 % Only.        Nodularity increased to 21 %

In post inoculation it is also important to have control over the nodularity.

**Magnesium: Sulphure Ratio-** It is controlled by addition of late sulphur addition along with inoculant to suppress formation of graphite nodules and to have high quality of Compacted Graphite Iron having compacted graphite in the range of 95-97 %.

Table No.7 The chemical analysis of some inoculants and additions after Magnesium treatment for CGI:

| Inoculant | %Silicon | %Calsium | %Aluminium | %Sulphure | % Iron |
|---|---|---|---|---|---|
| FeSi - 75 | 75.0-77.0 | 0.50-0.75 | 1.25-1.75 | None | Balance |
| ( CaSi ) | 62.0-65.0 | 28.0-32.0 | 2.25-2.50 | None | Balance |
| ( FeS ) | None | None | None | Yes | Balance |

**Some more Practical Tips on control on residual Magnesium:**

The melting aggregates to produce CG iron are in principle the same as those used for SG iron. Requirements of raw materials, superheating &desulphurizing before melt treatment are same as those for SG Iron. Ferro-Silicon-Magnesium alloy with 5-6 % Mg. can reduce the cost of magnesium treatment as amount of alloy required is less than ductile iron.CG is obtained when treating an SG-type base iron with magnesium-iron- silicon alloy, when residual magnesium is controlled in the range of 0.013 to 0.022%. This type of control is difficult to achieve in production runs.

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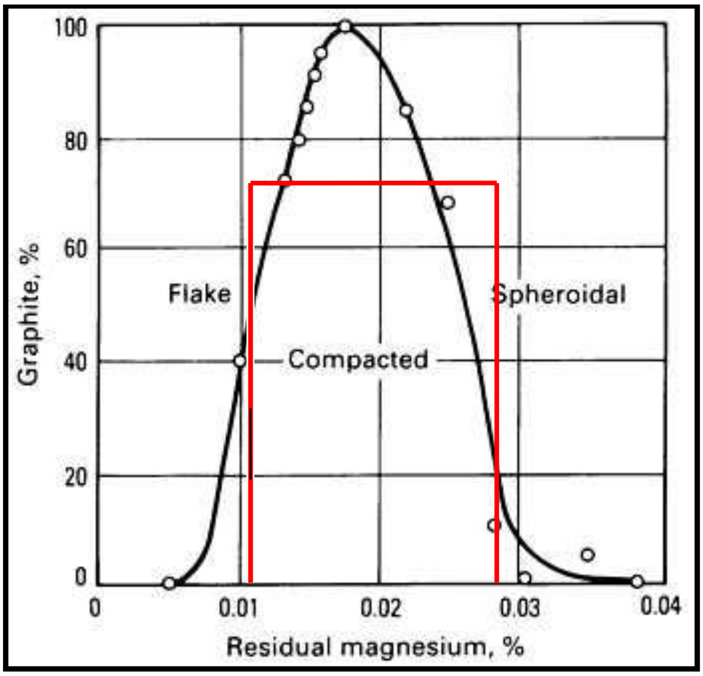
Figure -17. Relation of residual magnesium after treatment deciding the type of graphite:



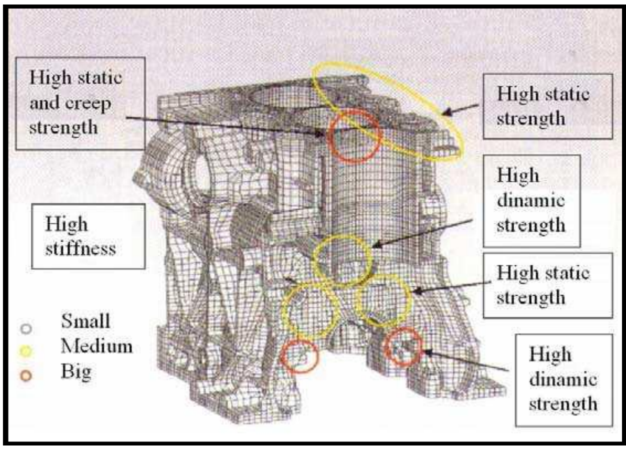

The above graph clearly shows the range of residual magnesium required for the production of compacted graphite iron. The lower magnesium contents are responsible for formation of flake graphite while higher magnesium promote nodule formation. The recovery of magnesium is also important and any magnesium treatment or process can be used for production of compacted graphite iron. The use of pure magnesium can also be used. One of the other vital points is the temperature of magnesium treatment as it will affect the formation of maximum % of compacted graphite.

**Applications of Compacted Graphite Iron**

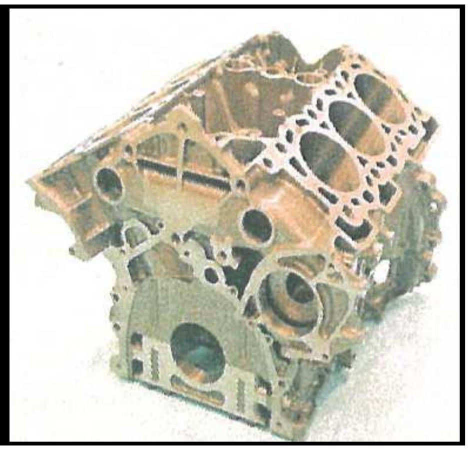
The applications of CG irons stem from their relative intermediate position between FG and SG irons. However, when the higher strengths of CG Iron are being used, then relative machinability is much better than both the FG and SG irons.

It may be also can be useful for the mining machineries used in Iron, Copper, Gold and coal mines in India and in world in countries like South Africa, Australia and other countries.

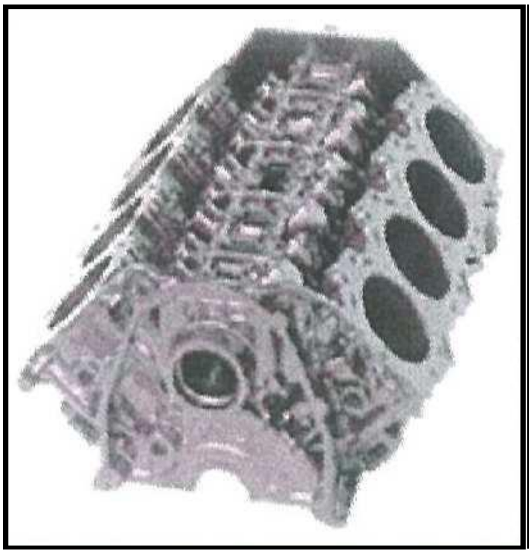
Figure –18.(A) (B) (C) & (D) Application of Compacted Graphite Iron Castings for Engines.




(A)



(B)



(C)


(D)

Modern car and truck engines require that exhaust manifolds work at temperature ranges of 500 °C. At this temperature, FG iron manifolds are prone to cracking, while SG iron manifolds tend to warp. CG iron manifolds undergo less warpage and oxidation and thus have a longer life.

The largest industrial application by weight of CG iron produced is for ingot moulds weighing up to 54 Mg (60 tons). The life of ingot moulds made of CG iron is 20 to 70% longer than the life of those made of FG iron.

## Conclusions

To achieve consistent high quality Compacted Graphite Iron castings it is utmost essential to have strict Process control on Chemical composition, Melting shop to give metallurgical quality metal, Magnesium Treatment to achieve required residual magnesium, Inoculation of treated metal and then the control on Pouring time of the treated metal.

Then the Mechanical Properties and Microstructure is checked in inspection department which decides if castings are accepted by the customer. Compacted graphite iron castings are certainly the material of the current century all over world.

**ACKNOWLEDGEMENT**

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**Other References from M/S Sintercast Ltd.**

1. All the Technical Information Data Engineering Source Book for C.G.I. given by Dr. Steve Dawson.
2. The Sintercast Ltd. U.K. Data sheets on Compacted Graphite Engineering Properties .
3. C.G.I. Technical Papers and research work done by their technical experts and Engineers.
4. Technical presentation of Dr. Steve Dawson on Compacted Graphite Technology from time to time.
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6. Personal relation with Dr. Steve Dawson who has helped me by giving case studies on
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8. Copy of original Patent reference of Compacted Graphite Iron.
9. Technical Presentation given by Sintercast representative at Pune, Maharashtra State, India.
10. Engineering Properties tables in various references on C.G.I.