

Vermicular graphite cast iron—current state of the art

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Abstract. Vermicular graphite cast iron is a new addition to the family of cast irons. Various methods for producing vermicular graphite cast iron are briefly discussed in this paper. The mechanical and physical properties of cast irons with vermicular graphite have been found to be intermediate between those of gray and ductile irons. Other properties such as casting characteristics, scaling resistance, damping capacity and machinability have been compared with those of gray and ductile irons. Probable applications of vermicular graphite cast irons are suggested.

Keywords. Cast iron; vermicular graphite; production; properties; micro-structure; applications.

1. Introduction

Cast irons, like steels, are basically alloys of iron and carbon. Gray cast iron is the oldest member of the cast iron family and the carbon in it exists in the form of graphite flakes. The main factor favouring the widespread use of gray iron is its low cost. Even though the tensile properties of gray iron are inferior, it possesses high compression strength coupled with excellent damping capacity. However, since its invention in 1947, spheroidal graphite cast iron (sg iron), with its high tensile strength and elongation, has been found useful in replacing certain steel components. In sg iron the graphite is present as nodules and the continuity of the matrix is much higher as compared to that in flake graphite gray iron, resulting in superior mechanical properties.

In vermicular graphite cast irons (vg irons), graphite is present in a worm-like, stubby form with rounded edges. This material is also popularly known as “compacted graphite cast iron or as cg iron”. Vermicular graphite cast iron was an accidental discovery during tonnage production of sg iron castings, and was initially considered a degraded form of iron. Subsequently, it has attracted much interest, and the intentional production of vg irons was first achieved by Estes and Scheidewind (1955). Subsequently various production methods and physical and mechanical properties were investigated in different countries (Sissener *et al* 1972; Sofroni *et al* 1974; Evans *et al* 1976; Lalich & LaPresta 1978; Green & Thomas 1979; Cooper & Loper 1978; Aleksandrov *et al* 1976).

vg irons have certain advantages over the older members of the cast iron family viz, gray, ductile and malleable irons:

- (i) The tolerable content of sulphur in vg iron is much higher than in ductile iron,
- (ii) The temperature range in which the reaction material is effective is very wide in vg iron as compared to sg iron,

- (iii) The amount of treatment alloy needed is quite low,
- (iv) An sg iron foundry can use identical production methods and materials for vg iron production also,
- (v) The production of vg iron does not mandate long heat treatment cycles as in the case of malleable iron,
- (vi) vg iron possesses a good combination of properties, thereby bridging the gap between gray and ductile irons.

The present article covers the methods of production and the physical and mechanical properties of vg iron, and reports the results of investigations carried out on some of the above aspects.

2. Production methods

At the present time, as a result of improvements in treatment materials, processing techniques and quality control, it is possible to produce vg irons commercially. Different proven methods for production of vg iron are given below.

2.1 Extensive desulphurization

Attempts to upgrade low strength irons by injecting calcium carbide lead to vg iron formation (Henderson & Hulms 1953). As the degree of desulphurization increases, graphite flakes get shorter and more compacted. Subsequently, they begin to curl to form the vermicular shape. Injection of calcium carbide, magnesium oxide and rare earths or calcium carbide and rare earth oxides to produce vermicular graphite result in varying degrees of success, but the cast irons produced have higher strength than gray iron (Estes & Scheidewind 1955). On the other hand, when pure Fe-C-Si alloy is severely desulphurised followed by rapid cooling (upto 112°C/min), the graphite formed is shorter and thicker with rounded edges (Prasad & Phelps 1966).

2.2 Controlling the nitrogen content

Nitrogen is commonly present in all cast irons in small amounts, and nitrogen content has been proved to influence the graphite structure (Sergeant & Evans 1978). It is believed that nitrogen segregates in the liquid ahead of the advancing solid interface; a diffusion barrier for the addition of atoms is created resulting in the desired under cooling. Thus, controlled amounts of nitrogen can lead to different forms of graphite; the only problem in this method is that control has to be effected very accurately, lest the gas content should go up to result in blow holes and similar defects.

The above two methods are not very useful in repetitive commercial production; alternatively, the following treatment methods have been successfully employed for the production of vg iron castings.

2.3 Deliberate undertreatment

In ductile iron production, a residual magnesium content of 0.05–0.06% is usually aimed at. On the other hand, for vg iron production complete spheroidization is not allowed to take place. An insufficient amount of magnesium is added (0.01–0.02%) so that the reaction in the melt is just initiated (but doesn't reach completion) to produce

vermicular graphite. This treatment is effective only if the Mg content is maintained within the narrow range of 0.01–0.02%. Such a treatment method is slightly difficult to adopt for large production.

The low melting point and high volatility of magnesium explain its ease of diffusion through the melt; its fading time is quite low. The rare earths, on the other hand, with their high boiling point and volatility, have somewhat slower diffusion rates, but are less prone to fading. Hence, individual treatment with rare earths or with the combination of rare earths and magnesium can be adopted for the production of VG irons (Kimura *et al* 1981). Rare earth elements can also act as scavengers of impurities and increase the fluidity of the melt. The effect of holding time on irons treated with rare earth materials (Kimura *et al* 1981), the importance of the lanthanum/rare earth ratio in the treatment alloy (Stefanescu *et al* 1981), and the effect of cerium and calcium in the production of vermicular graphite cast iron (Simmons & Briggs 1982) have been investigated in detail.

2.4 Combined treatment

In this method, the molten iron is first treated with magnesium ($\approx 0.02\%$ residual) and subsequently with small amounts of antispheroidizing elements such as titanium, aluminium (0.05–0.07% residual) etc. The amount of anti-spheroidizing elements varies based on the degree of denodularization required. The purpose of adding magnesium is to initiate the spheroidization reaction, which is arrested before completion by the appropriate amounts of anti-spheroidizing agents. The calculation of the amounts of spheroidizing and antispheroidizing elements has been discussed in detail (Sofroni *et al* 1974). For a given anti-spheroidizing agent, the degree of denodularization can also be calculated (Kozhinkii 1976). Many master alloys have been developed and are available under proprietary names (e.g. the alloy of the Foote Mineral Co.). Control is much easier in this method than in the other methods discussed.

2.5 Treatment with elements such as Zr, Pb, Sn etc

When magnesium undertreatment is adopted, for instance, the conditions under which the graphite can form are restricted to some extent. Even very small deviation in chemical composition and in treatment temperature may lead to deviation from vermicular graphite formation. It has been found that treatment with zirconium results in a structure which is almost like vermicular graphite i.e. coral graphite. This method of processing, however, suffers from the disadvantage that the sulphur content of the melt should be very low (of the order of 20–30 ppm).

2.6 Mg treatment coupled with gas blowing

On blowing various gases such as methane, argon, nitrogen, acetylene and air into molten iron which has already been treated with magnesium, the graphite shape changes from spheroidal to vermicular. This is because of the increased fading effect of the bubbling gases. Optimum vermicular graphite structure is reported when the gas is blown into molten metal at about 1420°C (Tsutsumi *et al* 1981). Among various gases, methane and acetylene give maximum vermicular graphite. It is believed that these gases contribute towards nucleation as well as fading (Tsutsumi *et al* 1981).

3. Microstructure

The typical microstructure of VG iron is shown in figure 1. The graphite shape can be seen to be intermediate between flake and spheroidal. It is quite possible to obtain a structure exhibiting a combination of vermicular and flake graphite or of spheroidal and vermicular graphite. The thickening and rounding of the graphite particles in vermicular graphite cast iron tends to lower the stress concentration at the graphite-metal matrix interface compared to flake graphite. Due to the intermediate shape of this graphite (intermediate between flake and spheroid), the mechanical properties are also expected to be intermediate between those of gray and ductile irons.

VG irons are classified based on the length to thickness ratio (aspect ratio) of the graphite, and such classification is given in table 1. The vermicularity of graphite can be calculated using the following formula (Loper *et al* 1980):

$$\% \text{ vermicularity} = 1 - \% \text{ nodularity}$$

$$\% \text{ nodularity} = \frac{\text{number of graphite particles of types I \& II}}{\text{number of graphite particles of types I, II, III \& IV}}$$

where, types I, II, III and IV are true spheroids, essentially spheroids, vermicular graphite, and branched versions of type III respectively.

By changing the melt treatment and composition, it is possible to change the matrix, viz, ferrite, pearlite and different mixtures of ferrite and pearlite. It is also possible to obtain different structures such as bainite, martensite etc. by subjecting VG irons to different heat treatments.

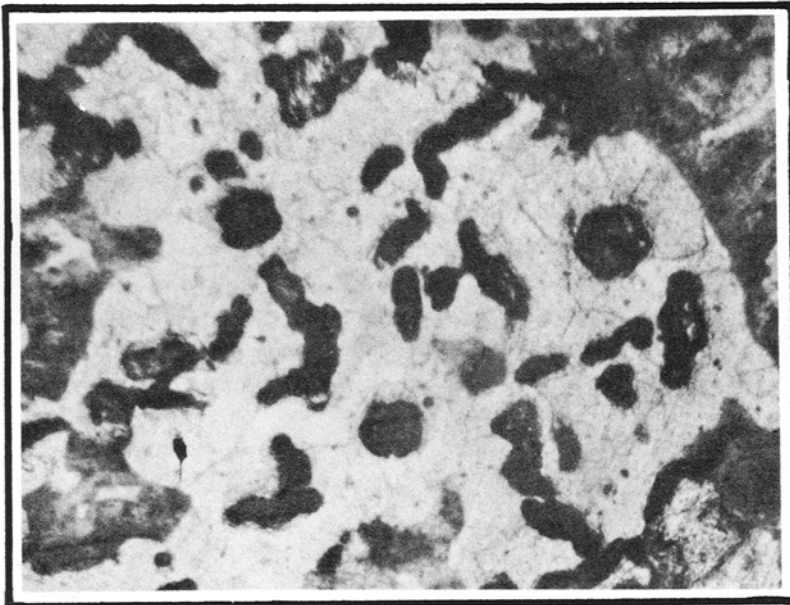


Figure 1. Microstructure of vermicular graphite cast iron (400 ×)

Table 1. Classification of vermicular graphite cast irons (after Safroni *et al* 1974)

Type of vermicular graphite	Dimensional characteristics of graphite			Mechanical properties of VG cast irons			Remarks
	Maximum length (l) μm	Maximum thickness (t) μm	l/t	Tensile strength MPa	Percent elongation	Hardness BHN	
Type I	20	10	2-4	300-450	2-5	150-240	Similar to ASTM-D form
Type II	150	50	2-5	350-500	3-9	150-240	Similar to ASTM-M form
Type III	150	20	3-10	300-450	1-3.5	150-250	Similar to ASTM-P form

4. Graphite growth and morphology

Even though vermicular graphite looks like an isolated, individual particle, in a three dimensional matrix graphite is interconnected within the eutectic cell (Lalich & LaPresta 1978). It is evident from morphological studies by deep etching techniques that vermicular graphite grows in a spiral manner (figure 2). There are at present two concepts on the growth of vermicular graphite viz, (i) growth in the *A* and *C*-axis directions, and (ii) growth in the *C*-axis direction alone. However, extensive work on graphite in VG cast irons has shown that *C*-axis growth alone is prevalent, perpendicular to the basal planes of graphite crystals, similar to that of spheroidal graphite (Liu *et al* 1981; Murthy *et al* 1985).

5. Casting characteristics

Good quality castings of VG iron can be produced repetitively. Producing sound castings of VG iron is easier compared to ductile irons but slightly more difficult than gray irons. Running and feeding systems designed for gray irons have been reported to produce sound VG iron castings. However, it has also been suggested that gating and feeding system design should follow the procedures adopted in ductile iron foundries. Fluidity of VG iron is equal to that of any other iron, and the fluidity is independent of the final graphite structure (Sergeant *et al* 1978). Shrinkage was found to be less as compared to ductile irons (Athavale *et al* 1983). Due to the lesser magnesium content used in treatment, dross formation is also lower.

6. Mechanical and physical properties

6.1 Tensile strength and elongation

In gray iron, graphite flakes act as stress raisers, and consequently gray iron exhibits low tensile properties. When the graphite flakes start getting shorter and rounded (as in VG

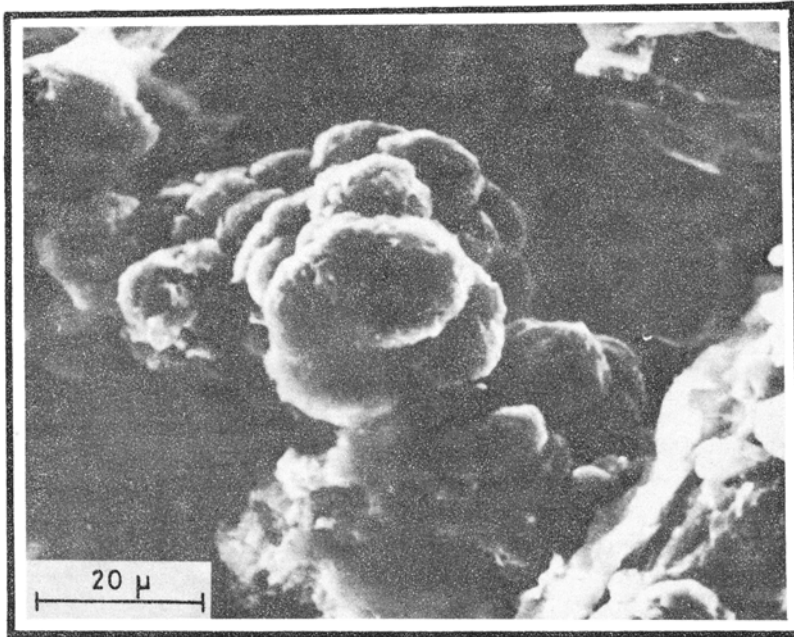


Figure 2. SEM photograph showing spiral growth of vermicular graphite.

iron), the properties improve, and measurable elongation and higher tensile strength are realised. Ductile iron with its rounded spheroids is inherently stronger due to total absence of stress raising action.

A comparison of the tensile strength and elongation values of the three cast irons viz, gray, vermicular, and ductile irons along with other properties such as elastic modulus and yield strength is made in table 2.

The influence of carbon equivalent, silicon content, phosphorus content and % nodularity on mechanical properties of vg iron is shown in figures 3, 4, 5 and 6 respectively.

Table 2. Mechanical properties of different cast irons

Property	Gray	Vermicular	Spheroidal
Tensile strength (MPa)	150-400	350-650	400-800
Yield strength (MPa)	-	270-300	250-400
% Elongation	-	3-10	5-20
Hardness (BHN)	120-145	130-180	200-250
Elastic modulus $\text{MPa} \times 10^3$	80-140	140-160	160-185
Notched impact strength (kgm)	0.15-0.18	0.22-0.31	0.40-0.45
		gray iron base	
		0.32-0.38	
		ductile iron base	
Thermal conductivity $\text{W m}^{-1} \text{k}^{-1}$	210-58-280-50	175-41-221-88	105-08-175-42

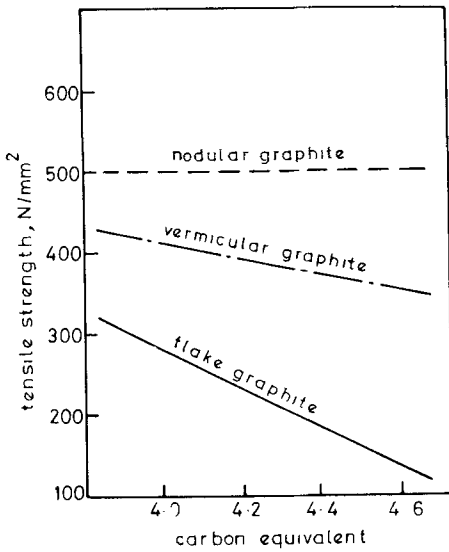


Figure 3. Influence of carbon equivalent on tensile strength of flake, vermicular and nodular graphite irons (after Sergeant & Evans 1978)

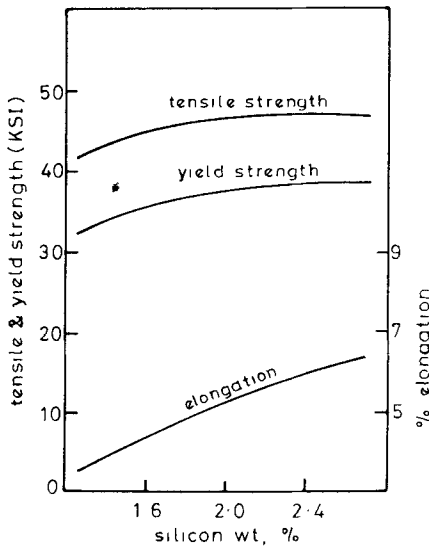


Figure 4. Effect of silicon on the mechanical properties of VG iron (after Cooper & Loper 1978)

6.2 Hardness

Hardness of VG iron has been found to be intermediate between that of gray and ductile irons for identical matrices (table 2). Any carbide formation leads to enhancement of the hardness value. The relation between hardness and percentage pearlite content is shown in figure 7.

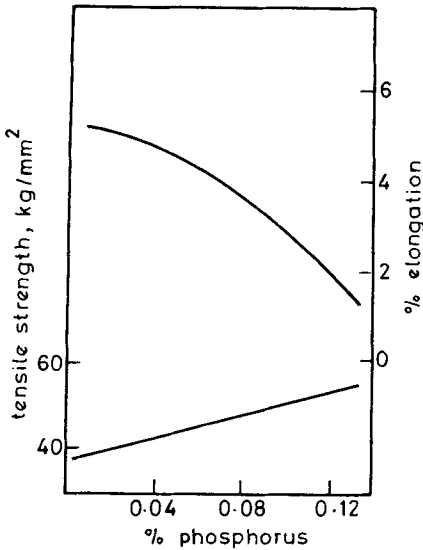


Figure 5. Effect of phosphorus content on the mechanical properties of vermicular graphite iron (after Aleksandrov *et al* 1976)

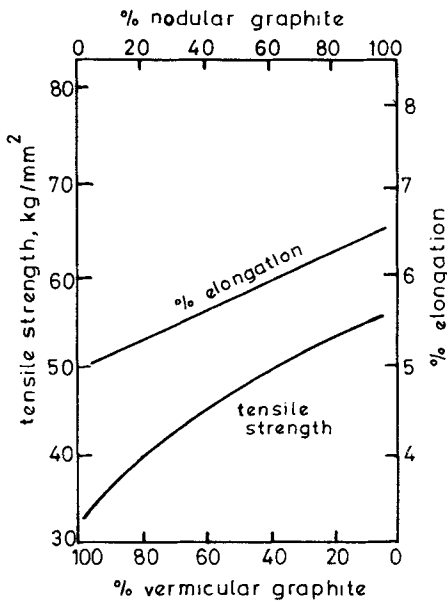


Figure 6. Variation of tensile properties with the percentage of nodular graphite in VG iron (after Aleksandrov *et al* 1976)

6.3 Impact strength

The charpy impact test results are shown in table 2. Examination of the values of the energy for breaking makes it clear that vermicular graphite coexisting with nodular graphite absorbed greater energy than the one with flake graphite. Pearlitic vermicular graphite cast irons have impact strength almost equal to that of ferritic ductile irons.

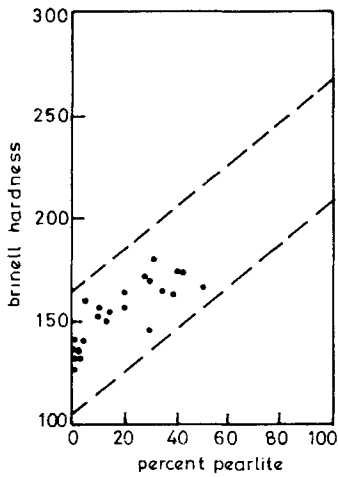


Figure 7. Variation of hardness with pearlite content in VG iron (after Loper *et al* 1980)

The appearance of the fractured surface of VG irons changes from dark to light gray with transition from ductile to brittle failure.

6.4 Fatigue

Fatigue properties, in reversed bending, for notched and unnotched pearlitic VG irons are illustrated in figure 8. The endurance ratio (ratio of unnotched fatigue to tensile strength) is about 0.45, and is influenced by the matrix structure.

6.5 Damping capacity

Damping capacity is the ability of a material to absorb vibrational energy. The damping capacity of VG iron has been found to be a compromise between gray and ductile irons (table 3). The damping capacity level achieved in VG irons does represent a marked improvement over nodular iron, and owes this improvement to the interconnected nature of the graphite.

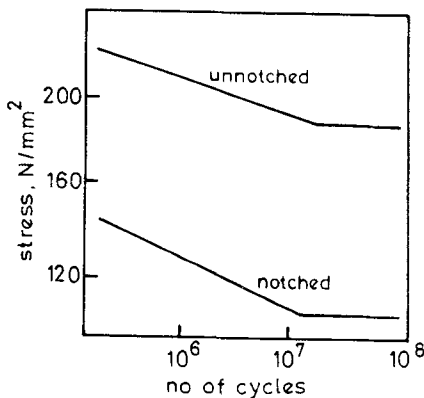


Figure 8. Fatigue curves for pearlitic VG cast irons (after Sergeant & Evans 1978)

Table 3. Sonic damping capacity of pearlitic vermicular graphite cast irons (after Sergeant & Evens 1978)

Carbon equivalent		Cast section size (mm)				
		15	30	53	44.5 keel	200
4.0	Damping capacity $\times 10^{-4}$ }	4.0	4.6	5.0	5.0	7.3
4.3		4.0	4.3	4.3	5.0	6.3

6.6 Machinability

Several methods are in vogue for assessing the property of machinability viz, measurement of (i) drilling thrust, (ii) wear of tool, (iii) number of chips/gram, (iv) temperature of tool, (v) drill life etc. The machinability of ferritic and pearlitic VG irons were determined along with those of gray and nodular irons using some of the above methods. It is concluded that machinability of VG irons rates between that of gray and ductile irons (Philips 1981; Athavale *et al* 1983). Figure 9 shows the relative rating.

6.7 Wear resistance

In order to study wear behaviour of VG irons, experiments were conducted under dry friction conditions (Murthy *et al* 1985). The percent weight loss for different cast irons at constant speed, distance and normal load shown below is self explanatory.

Material	% weight loss
Ductile iron	12-15
VG iron	18-33
Gray iron	35-40

6.8 Thermal conductivity

Because of the interconnected nature of graphite in VG irons its thermal conductivity is superior to that of ductile iron, but lower than that of gray cast iron. The thermal conductivity values of different irons are given in table 2; VG irons which possess good wear resistance coupled with good thermal conductivity are ideally suited for specific uses such as brake components.

6.9 Growth and scaling

VG iron behaves satisfactorily at elevated temperatures as well. The growth and scaling characteristics of gray and VG irons heated in air to 600°C are shown in figure 10.

6.10 Corrosion

Investigations carried out by the authors to study the corrosion resistance of VG iron in dilute sulphuric acid show that VG iron's corrosion resistance is satisfactory, and is intermediate between that of gray and ductile irons.

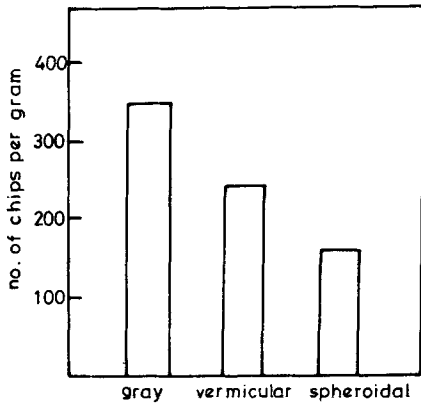


Figure 9. Machinability of gray, VG and SG irons.

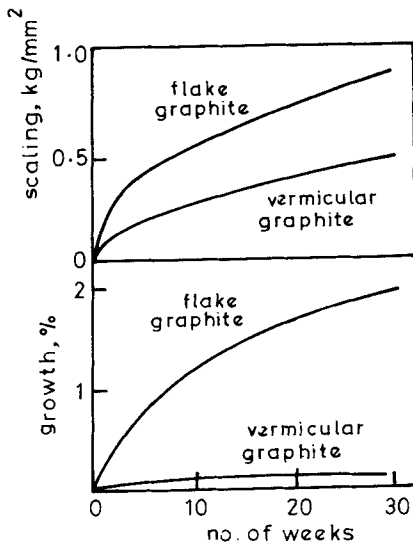


Figure 10. Growth and scaling characteristics of gray and VG iron at 600°C (after Green & Thomas 1979)

7. Applications

Interest in these irons has multiplied in recent years, and now industries are attempting to substitute several components by VG iron castings; a brief list of parts being substituted thus is given below:

Eccentric gear, transmission housing, exhaust manifold for 4-stroke engine, bearing bracket, sprocket wheel, chain wheel for scraper plate on heavy duty truck, inner shoe for tractor mover, tractor crank gear case, brake rotors for high speed trains, RCC sleeper insert and tractor differential case.

8. Conclusions

There are different methods available for repetitive production of VG irons, viz, extensive desulphurization, combined treatment with spheroidizing and anti-spheroidizing elements, treatment with Zr and blowing of gases into magnesium treated molten iron; some of these methods are quite suitable for large scale commercial production. Studies on graphite morphology show that vermicular graphite grows spirally in the C-axis direction of graphite crystals. VG irons exhibit physical and mechanical properties intermediate between gray and ductile irons and are finding newer applications in several fields.

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