Compacted graphite irons: high-quality engineering materials in the cast iron family

by I. C. H. Hughes & J. Powell

Synopsis—The range of properties of compacted graphite cast irons lies generally intermediate between those of flake graphite and nodular graphite cast irons, and makes them attractive for a number of applications. These properties arise from the unique compacted graphite structure. The alternative ways of producing compacted graphite cast irons are reviewed, and the potential for widening the range of properties through structure control is discussed. Of particular importance for commercial exploitation is quality control of the production process and of the material structure and properties, and the paper contains information on these topics. (Paper given at the SAB Earthmoving Industry Conference, Peoria, Illinois, 9–11 April 1984.)

Compacted graphite irons fulfil a need

Cast irons are, perhaps, the most widely used and versatile of any family of engineering materials, having a great range of mechanical property combinations which has not yet been fully exploited in production and by engineers. They are found in service in countless applications ranging from components for non-demanding applications to special castings having exacting as-cast shapes with combined critical performance specifications unmatched by other materials and with very advantageous cost-benefit relationships. Cast iron uses extend from internal combustion engines to grinding media for ore-crushing mills, from steelworks components and ingot moulds to high-strength gears for automotive service, and from marine engine crankshafts to insulator caps for power transmission lines.

In 1949 ductile iron (also referred to as nodular or spheroidal graphite cast iron) was invented and enabled the range of as-cast strengths to be increased from the then maximum of about 180 N/mm² up to 410 N/mm² and more, with considerable as-cast ductility and opportunity for further increase in properties through heat treatment. Compared with grey engineering irons, however, ductile iron has the disadvantages of lower thermal conductivity, and a need for greater care in moulding, and the design of running and feeding systems to achieve sound castings in some more complicated shapes.

Compacted graphite irons, which have become commercially available in recent years, have a range of properties which lie between those of grey and nodular irons and therefore in many respects combine desirable qualities of both. There have been many published papers which report the structure and properties of compacted graphite irons, but the outstanding characteristics of these materials may be summarized as: good thermal conductivity combined with useful ductility, higher tensile and fatigue strengths than for grey irons, and foundry properties which make it easier to achieve sound castings than for ductile irons.

The increased strength of compacted graphite irons has been partially exploited for some considerable time through the deliberate or incidental use of nitrogen in high-duty grey irons, generally produced from steel scrap charges, but this process is only of limited application and other methods of production are used as described later. Early major commercial application of these materials was in the manufacture of ingot moulds for steelworks, where for certain designs, their thermal conductivity and resistance to distortion and major cracking proved to be beneficial, and this application has continued to involve the production of a large tonnage of castings.¹ The behaviour under stress at elevated temperatures has, however, encouraged many other applications involving such components as internal combustion engine cylinder heads,² brake drums and discs,³ exhaust manifolds⁴ and piston rings.⁵ Their good combination of strength and feeding behaviour have also led to their application for heavy cored castings such as hydraulic valves, which are increasingly requiring strengths in excess of those provided by traditional grey engineering irons but

![Fig. 1 The effect of carbon equivalent on the tensile strengths of flake, compacted and nodular graphite irons cast into 30 mm diameter bars.](image-url)
are costly to obtain sound in ductile iron. Other applications have been reviewed by Nechtelberger and others.2

Properties of compacted graphite iron
A considerable literature reports many properties of compacted graphite irons, and a few papers contain especially useful summaries.3,7,8,9 There are, as yet, no issued standards for these materials and it seems likely that well-established and accepted property ranges will be agreed only as a result of wider experience of their manufacture and use. In the present paper some data are given illustrating a number of the more interesting properties likely to be of importance in promoting applications for which compacted graphite irons may be specially suitable.

Table 1 A comparison of the tensile strengths and thermal conductivities of a flake, a compacted and a nodular graphite cast iron.

<table>
<thead>
<tr>
<th></th>
<th>Tensile strength, N/mm²</th>
<th>Elongation %</th>
<th>Thermal conductivity, W/m·K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flake graphite iron</td>
<td>220</td>
<td>0·63</td>
<td>50·1 – 46·1</td>
</tr>
<tr>
<td>Compacted graphite iron</td>
<td>400</td>
<td>1·5 – 4·5</td>
<td>43·0 – 36·0</td>
</tr>
<tr>
<td>Nodular graphite iron</td>
<td>500</td>
<td>7 – 15</td>
<td>35·5 – 34·9</td>
</tr>
</tbody>
</table>

![Graph showing tensile stress versus strain for flake, compacted, and nodular graphite cast irons.](image)

**Fig. 2** Influence of graphite form on the stress-strain curves of cast irons.

**Fig. 3** Influence of graphite form on the modulus of elasticity of cast irons.

On stressing of compacted graphite iron in tension, the stress/strain relation shows much less curvature from the origin than that for a flake graphite iron, although a considerable straight-line portion as occurs for nodular graphite irons may not be exhibited. This is illustrated by the stress/strain curves in Fig. 2.10 The degree of compaction of graphite can vary, and as the graphite becomes more compact so the strain resulting from a given stress becomes less, as is shown for the three curves for compacted graphite irons in Fig. 2.

As for flake graphite irons, the strain resulting from tensile stressing may be subdivided into recoverable and non-recoverable strain, and the relation between recoverable and non-recoverable strain, measured at any given stress, may be expressed as a modulus of elasticity, which falls with increasing stress, as is shown in Fig. 3. The rate of fall of
modulus of elasticity with increasing stress is much less than for flake graphite irons, and decreases with increasing compaction of the graphite. The modulus of elasticity at zero stress, or E₀ value, may be determined by extrapolation or by resonant-frequency or ultrasonic-velocity measurements, as discussed later, and this increases with the degree of compaction of the graphite. As for all cast irons, the modulus of elasticity falls with increasing graphite content, usually expressed in terms of increasing carbon equivalent.

Rotating-bending fatigue properties on typical cast irons have been determined by Palmer²¹ and are compared in Table 2. In the unnotched condition the endurance ratios for all types of cast iron are similar at 0.45, but compacted graphite irons are more notch-sensitive than flake graphite irons and in the V-notched condition the strength-reduction factor is similar to that of nodular graphite irons. The effect of notch-root radius is illustrated for both nodular and compacted graphite irons in Fig. 4, which shows that less severe notches have relatively much less adverse effect. Care must be exercised however to avoid the notch effect caused by sharp edges to any machining marks which have not been well blended.

More detailed values for thermal conductivity are given in Table 3, showing how this property varies with increasing temperature. These values will also be increased as the amount of graphite in the structure, or the carbon equivalent, increases.

At elevated temperatures the compacted graphite irons maintain their strength and elongation well, up to about 400 °C, in which respect they resemble flake graphite irons. This is illustrated in Fig. 5 while Table 4 suggests elevated-temperature design stresses for different kinds of cast iron. Growth and scaling occur to a much less extent than in flake graphite irons, as is illustrated by Fig. 6 for continuous service at 600 °C. BGIRA uses a thermal

Table 2 Comparison of the fatigue strengths of pearlitic cast irons.

<table>
<thead>
<tr>
<th>Type of cast iron</th>
<th>Tensile strength, N/mm²</th>
<th>Unnotched</th>
<th>V-notched</th>
<th>Fatigue limit, N/mm²</th>
<th>Fatigue limit, N/mm²</th>
<th>Fatigue-strength reduction factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flake graphite</td>
<td>260</td>
<td>117</td>
<td>0.45</td>
<td>108</td>
<td>1.08</td>
<td></td>
</tr>
<tr>
<td>Compacted graphite</td>
<td>414</td>
<td>185</td>
<td>0.45</td>
<td>108</td>
<td>1.72</td>
<td></td>
</tr>
<tr>
<td>Nodular graphite</td>
<td>630</td>
<td>284</td>
<td>0.45</td>
<td>106</td>
<td>1.70</td>
<td></td>
</tr>
</tbody>
</table>

Table 3 A comparison of the thermal conductivity of a flake, a compacted and a nodular graphite cast iron.

<table>
<thead>
<tr>
<th></th>
<th>Thermal conductivity, W/m·K</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>100 °C</td>
</tr>
<tr>
<td>Flake graphite iron</td>
<td>48.8</td>
</tr>
<tr>
<td>Compacted graphite iron</td>
<td>41.0</td>
</tr>
<tr>
<td>Nodular graphite iron</td>
<td>35.5</td>
</tr>
</tbody>
</table>

Fig. 4 The effect of notch-root radius (r) on the fatigue limit of cast irons with mixed ferrite/pearlitic matrix, tested in rotating bending, using specimens of diameter (d) 10·6 mm.

Fig. 5 High-temperature tensile properties of a pearlitic compacted graphite iron.
Table 4 Tensile design stresses for pearlitic flake, compacted and nodular graphite iron.

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Compacted graphite (tensile strength 400 N/mm²), N/mm²</th>
<th>Flake graphite (UK Grade 260), N/mm²</th>
<th>Nodular graphite (UK Grade 600/3), N/mm²</th>
</tr>
</thead>
<tbody>
<tr>
<td>°C</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>103</td>
<td>66</td>
<td>148</td>
</tr>
<tr>
<td>100</td>
<td>94</td>
<td>57</td>
<td>131</td>
</tr>
<tr>
<td>200</td>
<td>89</td>
<td>69</td>
<td>130</td>
</tr>
<tr>
<td>300</td>
<td>92</td>
<td>83</td>
<td>130</td>
</tr>
<tr>
<td>Basis for design stress</td>
<td>0.38 x (0.1 per cent proof stress)</td>
<td>0.35 x (0.1 per cent proof stress)</td>
<td>0.45 x (0.1 per cent proof stress)</td>
</tr>
</tbody>
</table>

Distortion and cracking test for cast irons to evaluate their likely elevated-temperature performance in service. Fig. 7 illustrates how, in this test, compacted graphite irons showed a better combination of resistance to crazing, distortion and cracking than either nodular or flake graphite cast irons.

In creep tests carried out at 350 °C on pearlitic unalloyed cast irons, compacted graphite irons have withstood 30 per cent or 40 per cent higher stresses than flake graphite irons to produce a given degree of creep in a given time; these stresses have been found to be about 75 per cent of those withstood by nodular graphite irons, as is shown in Table 5.

Fig. 8 illustrates some creep results at 350 °C.

Table 5 Creep data on different cast irons at 350 °C.

<table>
<thead>
<tr>
<th>Creep strain in 10 000 h %</th>
<th>Stress, N/mm²</th>
<th>Grey iron</th>
<th>Pearlitic malleable iron</th>
<th>Pearlitic nodular iron</th>
<th>Pearlitic compacted graphite iron</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>100</td>
<td>100</td>
<td>114</td>
<td>178</td>
<td>138</td>
</tr>
<tr>
<td>0.5</td>
<td>165</td>
<td>222</td>
<td>270</td>
<td>193</td>
<td></td>
</tr>
<tr>
<td>1.0</td>
<td>247</td>
<td>207</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 6 Growth and scaling of a flake graphite and a compacted graphite iron at 600 °C.

Fig. 7 Comparison of the performance of heavy-section irons in the BCIRA distortion and cracking test.

Fig. 8 Creep behaviour of a pearlitic compacted graphite iron at 350 °C.

Matrix structures:

F = ferritic
P = pearlitic
FP = ferritic/pearlitic

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Fig. 9 Charpy impact transition curves for a ferritic compacted graphite iron.

Although compacted graphite irons have less ductility than nodular irons, they exhibit a similar impact-ductility transition over a range of temperature. This is more sharply defined for the unnotched than for the notched condition, as is shown in Fig. 9. In Fig. 10 samples fractured over a range of temperature exhibited a characteristic change in the fracture appearance from a darker colour above the transition range to a lighter appearance below the range.

Fig. 10 Appearance of fracture surfaces of compacted graphite iron impact test pieces.

To produce sound castings for a given mould, more feeding is necessary for nodular irons than for flake graphite irons; this always presents a problem for foundrymen required to increase the strength of complex castings by changing from flake graphite to nodular graphite iron. Now compacted graphite irons, while providing much higher strengths than flake graphite irons, require appreciably less additional feeding than do nodular irons; Fig. 11 illustrates this by comparing the feed-metal requirements in terms of piping in a test casting produced at different temperatures using different types of iron.

For engineering castings, changing from one grade of cast iron to another often has repercussions in the machine shop. All engineering cast irons have good machinability, but there is no universally valid means of comparing machinability because relative behaviour changes with changes in the many variables involved in machining. However, Fig. 12 gives the

Fig. 11 Feeding needs of test castings made in greensand moulds.

results of some drilling tests which not unexpectedly showed that compacted graphite irons and nodular graphite irons produced only slightly greater wear of tools than flake graphite irons, when they had a good proportion of ferrite in the structure. When the matrix was substantially pearlitic both nodular and compacted graphite irons produced similar increased tool wear.

Relation between structure and properties
The as-cast properties of the engineering cast iron family depend principally upon the fact that they contain graphite in their structure, which can assume a wide variety of forms, and as their name implies, compacted graphite irons owe their special properties to graphite in a form intermediate between flake and nodular. The graphite is characterized by occurring in branched clusters of shortened, thickened flakes with rounded and often irregular edges. It is the branched structure which confers good thermal conductivity, not obtainable when the graphite is in a nodular or spheroidal form, while the rounded and compacted outline of the individual branched flakes greatly reduces the notch effect which restricts the strength and ductility of flake graphite grey iron, and this feature confers the greater strength and ductility of compacted graphite iron. Fig. 13 illustrates this form of graphite in a compacted graphite iron, revealed by etching away the matrix of metallic material and viewing under a scanning electron microscope. Viewed through a
As already pointed out, the degree of compactness of compacted graphite irons may to some extent be varied, depending on the manufacturing process, composition and casting size. As the degree of compaction increases, so the properties tend to approach those of nodular graphite iron rather than those of flake graphite iron. The degree of compaction is limited at one end of the scale by the occurrence of normal flake graphite, while at the other extreme the most compacted form of graphite occurs just before the appearance of graphite in nodular form. Since varying proportions of compacted graphite and nodular graphite can occur in the same sample, it is normal to manufacture with a maximum permitted nodular graphite percentage at which the properties are still characteristic of compacted graphite iron. This proportion is most commonly set at around 10 to 15 per cent nodular graphite, and will be referred to again later in connection with quality control.

Methods of producing compacted graphite irons

There are three different routes for the production of compacted graphite irons, each of which has been known for a long time, although in recent years a number of variations of these processes have been proposed. The main routes however are as follows.

The cerium process—Morrogh showed that when cerium mischmetall was added to cast iron in a sufficient amount to combine with the sulphur present and to provide a small excess of about 0.015 to 0.02 per cent, then compacted graphite could be obtained, which he called quasi-flake graphite. Morrogh in 1949 illustrated a compacted graphite iron containing 0.003 per cent sulphur and 0.05 per cent cerium, inoculated with ferrosilicon and having a tensile strength of 71,000 lb/in² (489·5 N/mm²). This method is still followed, and is operated by a number of foundries, particularly on the European Continent. The advantage of the process is that cerium is an easy element to add to cast iron with no problems of fume and flake, and the addition of cerium, usually as mischmetall, need not involve the addition of any other elements such as silicon or alloys. The amount of cerium to be added depends on the amount of sulphur in the iron, and obviously it is more economical to start with iron of a low sulphur content. As with the production of nodular iron, there is an advantage in using previously desulphurized metal or iron produced from low-sulphur charge materials such as steel scrap. A knowledge of the sulphur content is critical, and this element must be closely controlled for it to be possible to add the right amount of cerium. Production can be facilitated if the sulphur content has previously been deliberately reduced to a low value, and a practice of this kind has been described by Sissener. Figs. 15 & 16 illustrate the amount of cerium mischmetall (containing about 50 per cent cerium) to be added to achieve compacted graphite structures in two different irons made from different raw materials with varying initial sulphur contents, which illustrates that there is some small effect of raw materials on the results achieved.

An increasing excess of cerium over that required to combine with the sulphur content has a powerful chilling effect, though provided the cerium content is limited strong final inoculation with ferrosilicon or a similar material may be used to obtain carbide-free castings, and such inoculation is generally necessary especially in thinner sections. Furthermore, any excess of cerium over the minimum required to produce compacted graphite iron will, in the
presence of strong inoculation, lead to the production of a proportion of spheroidal graphite which may be undesirable. Much compacted graphite iron has been manufactured by the cerium route for the production of cylinder heads and other automotive castings, when it is generally necessary to carry out a heat treatment to ensure the absence of carbides in thin sections. A feature of the cerium process is a difficulty in obtaining fully pearlitic structures for maximum as-cast strength in irons treated by this means, and it may be necessary to add a number of minor elements, notably tin, antimony and copper, if a high-strength pearlitic structure is required.

The magnesium process—Compacted graphite is obtained as an intermediate stage in the production of nodular graphite iron when a critical amount of magnesium is retained in the iron but, as discovered by the earlier workers, control of this method using magnesium alone is commercially impracticable since either flake or nodular structures are very easily obtained through small variations in composition. The structure can however be obtained over a much wider range of compositions by combining with the magnesium an addition of titanium, which prevents the formation of the nodular graphite structure, while a wider range of good structures is achieved by addition of a very small amount of cerium in the process. It is possible to manufacture compacted graphite irons by initial treatment of the molten iron with titanium in the furnace, followed by treatment with magnesium alloy and by final inoculation with a silicon-containing material, making a small addition of cerium either with the magnesium or with the final inoculant. However, the successive use of additions with different alloying elements is tedious, and the process was greatly facilitated by the introduction of a single silicon-based magnesium/titanium/cerium alloy which enables a compacted graphite structure to be achieved by a single treatment operation, followed by inoculation with a silicon-containing inoculant. A later modification of the single alloy involved the incorporation of calcium to make it possible to treat irons with a wider range of sulphur contents. Like cerium, magnesium combines with any sulphur in the iron and magnesium sulphide is rejected as dross. An advantage of the combined addition alloy is its ability to treat irons of a fairly wide range of sulphur contents, and over-treatment is less likely to produce a chilling effect than over-treatment with cerium. On the other hand, over-treatment can lead to the formation of unwanted nodular graphite.

A disadvantage of this process lies in the fact that titanium may accumulate in return scrap to an extent which can prevent good compacted graphite structures being obtained, and the fact that titanium-containing scrap is undesirable in the production of other types of cast irons, particularly nodular iron, and must therefore be segregated in the foundry. Another problem lies in the fact that the magnesium will generally be added as a silicon-containing alloy and it is therefore difficult to obtain compacted graphite irons with a low silicon content by this process.

The magnesium process is the principal route used in America and the United Kingdom, and many thousands of tons of steelworks ingot moulds have been made by a controlled low magnesium variation of the process in Sweden and by the magnesium-titanium processes in the United Kingdom. Matrix structures can be ferritic, pearlitic or mixed according to the minor pearlite-stabilizing element contents. One characteristic of the magnesium-titanium single-alloy process is that it lends itself to operation by the Innomol process, and the alloy, which contains silicon, enables good inoculated structures to be obtained by that means. Improved recovery of alloying elements is obtained by that process, and fume and flare are eliminated.

The magnesium-titanium single-alloy process may be difficult to operate when the sulphur content of the iron is very low, owing to a danger of producing spheroidal graphite structures, and it has been suggested that the process is best operated when the sulphur content is deliberately kept above 0.02 per cent.

The nitrogen process—It has been known for many years that in grey cast irons nitrogen causes compaction of the graphite structure, especially in heavy sections. As the section size increases, a proportion of the graphite becomes very compact, and in very heavy sections a fully compacted graphite structure is produced. Irons made from steel scrap in the cupola have often had increased nitrogen contents, either because of the increased nitrogen content of the steel scrap or because of the more ready absorption of nitrogen from the coke by low carbon charges. Complete compaction of the graphite occurs only in very heavy sections, and many ingot moulds and other thickest-sectioned castings have been produced with compacted graphite structures by the appropriate selection of raw materials and cupola melting. In thinner-sectioned castings an increase in strength occurs with only minor compaction of the graphite. In recent times it has been found that a very reliable method of adding nitrogen has been the addition of nitrogen-containing ferro-manganese alloy. Nitrogen-containing irons usually have as-cast pearlitic microstructures, since nitrogen is a powerful pearlite stabilizer.

The disadvantages of nitrogen as a means of producing compacted graphite irons lie in the inability to produce uniform structures in castings of varying section size, and also in the danger that if more than about 0.008 per cent of nitrogen is present, then serious unsoundness and blowhole problems can result. It is therefore unlikely that this process will assume widespread practical significance in the foreseeable future.

Prospects for Improved compacted graphite irons

Apart from the control of the process for producing compacted graphite structures, there is scope for development in the properties of compacted graphite irons through the modification and control of the matrix structure. Most irons of this type have pearlitic, ferritic, or mixed pearlitic/ferritic matrices and these have only limited strength. For wear resistance a ferritic matrix would not be desirable, though it has been suggested that the presence of titanium carbide inclusions in castings made by the magnesium-titanium single-alloy route may provide improved wear resistance in brake discs and drums, following claims that the presence of this element can be desirable in grey iron braking-components.

The production of hardened-and-tempered matrix structures by heat treatment, for improving wear resistance, is already established for nodular irons and may provide some opportunity for achieving useful properties in compacted graphite irons. However, a more interesting proposition is the use of bainitic matrix structures through isothermal heat treatment and low alloying. Bainitic ductile irons have greatly enhanced strength and very useful combinations of strength, hardness and elongation. Such dramatic, though similar, upgrading of compacted graphite irons might be anticipated through similar alloying and heat treatment, and already the use of bainitic disc brakes having high strength and good thermal conductivity for use on high-speed vehicles has been
explored experimentally. This means of improving structure and properties should be more widely applied in the future.

Quality control

As in the production of any high-quality cast metal, good material and process control is necessary for the successful manufacture of compacted graphite iron castings. In general, a similar quality-control standard will be required to that normally exercised in any modern foundry producing good-quality ductile iron.

Compacted graphite structures are produced within fairly narrow ranges of composition and, therefore, careful selection of raw materials for melting is required, particularly in respect of sulphur content and trace elements such as chromium, tin, copper, antimony and other pearlite stabilizers. Phosphorus is avoided, since it can promote shrinkage problems with this as with other types of cast iron. In the magnesium-titanium process the titanium content of scrap must be monitored to avoid too great a build-up of this element in the charge. Carbon equivalent will generally be controlled to just below or around the eutectic value of 4.3 per cent.

Charges for melting and batches of metal to be treated should be carefully measured or weighed, and the correct amounts of addition alloys made to ensure that the desired final analysis is obtained. The metal sulphur content prior to treatment is important in the processes involving treatment with magnesium or cerium, and a prior desulphurizing treatment with calcium carbide or lime-containing materials is often used. For the cerium process, an initial sulphur content below 0.02 per cent is an advantage, while for magnesium-titanium treatment the initial sulphur content should be low but preferably not less than about 0.02 per cent in order to avoid nodular graphite formation. Sulphur analysis at this level presents little problem when using modern direct-reading analytical instruments.

The temperature of metal being treated is important. The recovery of the reactive elements magnesium and cerium falls if the treatment temperature is too high, while too low a temperature may lead to problems of inadequate solution of the addition material, especially of calcium-containing magnesium alloys. In the magnesium-titanium process the recovery of magnesium relative to that of titanium increases at low temperature, with the chance of nodular graphite formation.

The casting temperature, as with other cast irons, is controlled to the optimum for the castings being made. Very hot metal will lead to shrinkage problems, while too low a casting temperature can result in misrunning and failure to give sharp details in the casting, as well as problems of dross formation. The fluidity of compacted graphite irons is no different from that of other types of cast iron of the same carbon and silicon contents.

Good moulds lead to sound castings and are subject to well-established quality controls. Greensand moulds must be well-compacted, and many foundries employ chemically hardened moulds which yield the soundest castings with the minimum feeding requirements.

Because the elements used in the magnesium and cerium processes form sulphides and oxides during treatment of the metal, care must be taken to remove any slag formed before pouring, since if dirty metal is poured, particularly at low temperatures, dross problems similar to those sometimes experienced in nodular irons can occur.

The microstructure of castings is normally checked by means of suitable test coupons which are either cast separately or attached to the casting and subsequently removed. (Non-destructive tests are described later.) Particular attention must be paid to castings having a wide range of section sizes since, in irons made by the cerium or magnesium processes, as the section size decreases the compactness of the graphite increases and in small section sizes nodular graphite may be formed. Fig. 17 illustrates the effect of section size on strength of compacted graphite irons.

The effect of carbon equivalent on strength of compacted graphite irons is small, as is shown by Figs. 1 & 17.

Fig. 15 Graphite structures obtained using pure pig iron charge.

Fig. 16 Graphite structures obtained using carburised steel scrap charge.
However, at values higher than 4.3 there is an increasing risk of the occurrence of nodular graphite, especially in well-inoculated irons, and this is illustrated by the example of Fig. 18. Carbon equivalent also affects the chilling tendency in much the same way as in other cast irons; to a lesser extent than for ductile irons, but more so than for grey irons, as is shown by Fig. 19.

Compacted graphite irons are frequently produced in which some nodular graphite is present, and a proportion of such graphite can usually be tolerated and has been referred to above. Good control involves knowledge of the effect of increased proportions of nodular graphite and careful limitation of this variable. Some effects of increasing nodular content are illustrated in Figs. 20-24. The tensile strength and proof stress (yield stress) (Fig. 20), elongation (Fig. 21), modulus of elasticity (Fig. 22) and impact strength (Fig. 23) all increase with the presence of increasing nodular graphite. Thermal conductivity, on the other hand, falls with increasing nodular graphite, as is shown in Fig. 24. A useful general relation between thermal conductivity and tensile strength is shown in Fig. 25, and a knowledge of this enables iron to be chosen with a carbon equivalent yielding the desired property combination when both strength and thermal conductivity are important.

Thermal analysis is widely used to control carbon equivalent, carbon and silicon contents of molten irons prior to casting. This technique, which involves testing a small
Fig. 22 The effect of proportion of nodular graphite on the modulus of elasticity of compacted graphite irons.

Fig. 23 The effect of proportion of nodular graphite on the impact strength in the ductile range of compacted graphite irons.

Fig. 24 The effect of proportion of nodular graphite on the thermal conductivity of compacted graphite irons. A sample of molten iron prior to treatment and casting, may also be used for compacted graphite irons. There is a growing interest in the application of differential thermal analysis which extracts more information from a cooling-curve and is made practicable by the introduction of microcomputers.

Fig. 25 Relation between tensile strength and thermal conductivity for compacted graphite irons containing varying amounts of nodular graphite.

Fig. 26 Variation in resonant frequency of a test casting with amount of nodular graphite in a compacted graphite iron.

This type of analysis can be used for structure control of cast irons, and the technique has been described for compacted graphite irons by Steffes and others. Such a test could prove to be very valuable for foundries if it becomes adequately proved and generally available, since it will enable some guarantee of structure to be made earlier than the conventional examination of the finished product can be carried out.

The structure of compacted graphite iron castings may be checked and controlled by means of various non-destructive tests. The graphite structure may be evaluated by resonant frequency (sonic testing) measurements. This non-destructive testing technique will detect flake graphite on the one hand,

Fig. 27 Influence of graphite structure and section thickness on ultrasonic transmission velocity in cast irons.
and can be used to estimate the proportion of nodular graphite occurring at the other extreme of structure. This is shown in Fig. 26. The test can be applied to simple-shaped castings, and is already commonly used for the control of nodular iron castings. It has the disadvantage that each design of casting must first be calibrated to relate overall structure to resonant frequency.

Measurement of ultrasonic transmission velocity through a casting will provide a guide to graphite structure which does not require calibration for individual castings, although some small variation of response with section thickness is to be expected. Fig. 27 illustrates a general relation found for cast irons and, in general, ultrasonic transmission velocity values between 4.8 km/s and 5.2 km/s will be recorded on satisfactory compacted graphite iron castings.

The matrix structure of compacted graphite irons can be checked by existing well-known magnetic tests already used for other types of cast iron, which are not affected materially by variations in graphite form. The use of magnetic coercive force measurement and eddy current measurement on cast iron for evaluating the proportions of ferrite and pearlite have been described elsewhere, and similar results would be expected when the graphite is in the compacted form.

The future of compacted graphite irons

All new engineering materials are initially received by manufacturers and users with some reserve, and before they gain general acceptance there is a period during which they have to become proved, generally for an initial limited range of applications. Compacted graphite irons have become commercially established, and because they have desirable properties they are certain to become important additions to the range of engineering cast irons. During the initial period many foundries have been experimenting with their production and control, and a few have established themselves as major manufacturers of compacted graphite irons. It has become clear that production must take place under good technical control, and it is likely that production lines will generally operate on these materials exclusively if they are to be made most efficiently and economically. Perhaps it is unfortunate that the arrival of compacted graphite irons has coincided with world recession in the foundry industry and in those engineering industries which use cast iron components, so that their initial introduction has been slow. Nevertheless, as demand for high-quality iron castings returns, so the growth in use of compacted graphite irons may confidently be expected to resume for those applications for which their properties are clearly suited.

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