Theory and practice of feeding spheroidal graphite iron castings

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Composition, solidification and mould and casting design variables have been analyzed in their effects on shrinkage cavities in spheroidal graphite iron castings. It has been shown that within a limited selection among the process variables it should be possible, in principle, to obtain sound spheroidal graphite iron castings without feeders. In practice, however, it is simpler to control casting soundness by the use of feeders, the dimensions of which can be calculated by the modulus method. It has also been shown that correct feeder neck dimensioning is an important factor for proper feeder functioning.

INTRODUCTION

The remarkable rate of growth in the production of spheroidal graphite iron castings over the last two decades can be almost entirely attributed to the success of the foundry industry in resolving several complex technological problems which were encountered in the early stages of production. On the other hand, it is readily apparent from the technical literature in this field that certain problems arising in the current production of this alloy still remain which have not been fully resolved either in their technological or scientific context. The object of the present paper is to examine one such problem, namely the origin of shrinkage cavities in spheroidal graphite iron castings. In the first part of the paper some of the published research data on the subject will be reviewed. This will be followed by an examination of some recent results obtained by the authors. Finally, the technological approaches of overcoming shrinkage porosity will be discussed.

THE ORIGIN OF SHRINKAGE CAVITIES

General

From the published work on this subject it can be concluded that an explanation of shrinkage cavities in spheroidal graphite iron castings should be sought by considering three distinct groups of factors:

(a) volumetric changes occurring in the liquid state and during freezing,
(b) the macroscopic mechanisms involved in the liquid to solid transition within a casting,
(c) the dilation of the mould, and its dependence on the geometry of the casting and on the mould materials, in relation to the phenomena under (a) and (b).

Volumetric changes

Volumetric contraction of Fe-C and Fe-C-Si alloys in the liquid state has been measured by several investigators. Mühlberger has compared the available data for Fe-C alloys, Fig. 1. It appears from this data that the experimental scatter in the liquid volumetric contraction values lies between 2.1 and 4.3%. per 100°C. Such a wide scatter could be attributed to the combined effects of variations in experimental techniques and to the compositional differences of the alloys used. While Si does not appear to have a pronounced effect on the specific volume of liquid irons, the addition of Mg at 1300°C, according to Lepinskyh et al.2 raises the specific volume of an Fe-C 3-26, Si 3.3% alloy by 2.5%. Due to the fading effect of Mg additions, very few data on the direct measurement of volumetric changes in liquid spheroidal graphite irons are available apart from the work of Bold who gives 1% per 100°C for the value of the liquid volumetric contraction of spheroidal graphite iron (C 3.82, Si 1.77%). The scarcity and uncertainty of liquid contraction values of spheroidal graphite irons are thus apparent.

Whilst spheroidal graphite irons, in common with all

![Fig. 1—Specific volume changes in liquid iron-carbon alloys](image-url)
other alloys, contract during cooling in the liquid state, their behaviour during the freezing process is similar to that of flake irons, Fig. 2. The formation of graphite, with its high specific volume relative to that of the liquid from which it forms, may result in a net expansion during the freezing, and when the expansion due to graphite growth is larger than the contraction resulting from the growth of the austenite phase. According to Muhlberger, who used the Archimedes method of density measurement, this expansion for flake irons increases from 2 to 5% if the C or the carbon equivalent (C.E.%.) is raised from 3 to 4.5%. He reports that the expansion of a spheroidal graphite iron (only one alloy was tested in this condition) is twice as large as that of a flake iron of similar C.E.%.

Bold on the other hand, who used a ceramic mould for direct measurement of volume changes, gives a zero value for the volumetric change during freezing of a spheroidal graphite iron. Reynolds et al.4 who used an approximate method for measuring the total volumetric contraction of spheroidal graphite irons, state that no measurable shrinkage porosity occurs in irons of high C (or C.E.%). By implication these workers support Muhlberger, viz., that graphite expansion during freezing can compensate, under certain conditions of solidification, for the total and not only for the freezing contraction.

Solidification expansion of grey irons has been frequently measured using dilatometric techniques.4-7 The results obtained reveal two main features: (i) solidification expansion of a spheroidal graphite iron is 1.5 to 2 times larger than that of a flake iron of similar composition, and (ii) the magnitude of volumetric freezing expansion is alloy composition dependent and varies, between 0.5 and 2%.

On the evidence of the results available, the volumetric changes of spheroidal graphite irons can be summarized as follows:

- Liquid contraction may vary between 1 and 4-5%.
- At 100°C, the average reported values for eutectic iron lying between 1-0 and 2-0%
- Contraction values during freezing of a eutectic hypereutectic spheroidal graphite iron may vary from zero contraction to +6% expansion. No precise reasons for such wide variations in both groups of the reported results can at present be put forward.

**Microscopic and macroscopic morphologies of solidification of cast irons**

The bulk of published research on solidification of spheroidal graphite irons deals with two microscopic problems: mechanisms involved in producing nodular rather than flake graphite and the morphology of nodule growth. The former influences the shrinkage behaviour of spheroidal graphite irons during freezing, which is currently believed to occur in two stages.8-10 Hypereutectic nodules form initially and continue to grow during the eutectic freezing stage. During this stage the liquid is continuous throughout the casting and the expansion due to nodule growth is transmitted directly to the whole liquid. In the later stages of nodule growth some investigators consider that nodules become surrounded by an austenite envelope or sheath through which carbon diffuses for the nodules to continue to grow. From the point of view of the shrinkage behaviour of spheroidal graphite iron the second stage of freezing takes place which occurs in the latter stages of solidification, during which the liquid in contact with the austenite-nodule core is neither continuous nor connected with the liquid.
parts of the casting passing through the first stage of freezing. Any surplus expansion due to graphite growth in this second stage can cause macroscopic expansion of the casting either outwards to lead to mould dilation or inwards to prevent any central shrinkage cavities from forming. Volumetric expansion due to graphite growth and the macroscopic distribution of solid and liquid phases during the freezing process are thus directly related to both the shrinkage and the expansion behaviour of the mould as well as of the casting. The role which the mould materials and the casting design play in this process will be discussed in a subsequent paragraph.

Microscopic considerations of nodule growth alone cannot explain the shrinkage-expansion behaviour during freezing, without an examination of the basic causes for the variation in the macroscopic growth sequences within the casting. Several investigators have shown that the main origin of such variation lies in the rate of cooling of castings and ensuing temperature gradients.\textsuperscript{11,12,13} In a sand casting (2 to 12 cm thickness) three distinct zones have been observed (see Fig. 3): (i) the first zone appearing during freezing is largely liquid with some nodules and austenite grains dispersed through it, (ii) this is followed after 60 to 70\% of the completion of solidification by a predominantly spongy or mushy zone consisting of a continuous austenite network which is penetrated by the liquid containing graphite nodules, and (iii) finally, an austenite solid zone is established containing some enclosed graphite nodules as well as isolated liquid pockets carrying the remaining nodules. (Zones (i) and (ii) correspond to the first stage of freezing which is relevant to the shrinkage behaviour.) Each one of the three zones proceeds normally from the surface of the casting inwards and from the thinner towards the thicker sections. At any time during the freezing process the whole cross-section of a casting may contain one, two or all of the three zones. The way in which the depth and the movement of these three zones are related to the shrinkage-expansion behaviour of a casting will be considered in the discussion.

**Mould wall movement and casting design**

The fact, frequently observed, that the size of iron castings can often be larger than the size of the mould cavity in which the casting has been poured, has led many investigators to examine more closely the whole problem of mould wall movement or mould dilation. This work has been reviewed recently by Engler et al. and by Levekne et al.\textsuperscript{14,15}

![Fig. 3—Solidification sequences of spheroidal graphite iron](image)

![Fig. 4—Schematic representation of mould and casting wall movement, after Engler et al.](image)

who conducted a number of critical experiments in the field. The major findings of these and other workers can be summarized with reference to Fig. 4. Mould wall movement of a flat surface often starts inwards and is followed by an outward expansion. Both the direction and magnitude of such movements are influenced by the geometry of the mould cavity, the nature of the mould material, and the condition of mould compaction. The primary cause of mould wall movement is heat absorption and the resultant behaviour of sand grains and binders. The geometry of the mould cavity may alter mainly the direction of such movement.

In the case of flake and spheroidal graphite irons the casting itself plays a major part in the mould wall movement apart from solely being the source of heat. Whilst still liquid the casting follows the mould wall movement depending on the balance of metallostatic forces only. During freezing however the cast shape is also influenced by the contraction-expansion forces within the casting itself and which may exceed the mould forces. Contraction or expansion forces can be due to the cooling of the casting once this forms a solid skin, but the expansion forces could be augmented by graphite growth as discussed in the preceding paragraphs. As a net result of either source of forces, the expansion can occur outwards, causing mould dilation, or inwards, compensating for volumetric contraction in the central regions of the casting. The way in which the volume changes occurring in flake and spheroidal graphite iron interact with the mould has been recently investigated by Kochisen.\textsuperscript{16} He and other workers,\textsuperscript{13,17,18} have shown that both types of iron can cause mould dilation during the freezing process, the effect of spheroidal graphite iron being larger. This difference in expansion behaviour can be explained by the differences in the mode of growth and macroscopic distribution of solid and liquid during freezing. Flake irons solidify predominantly by the skin type of growth during which the expansion due to graphite can be transmitted to the liquid, thus largely balancing the liquid contraction. In the case of spheroidal graphite irons, on the other hand, the pasty zone predominates, and in particular the type characterized by the presence of isolated liquid pockets. Any expansion due to graphite growth in this zone can be passed either outward.
TABLE I  Main factors controlling shrinkage cavities

<table>
<thead>
<tr>
<th>Control variable</th>
<th>Process control factors</th>
<th>Shrinkage effects</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total volume contraction ( \Delta v_t \rightarrow \Delta t )</td>
<td>Alloy composition, melt treatments, pouring temperature</td>
<td>1. ( \Delta v_{\text{tot}} &lt; \Delta v_{\text{for shrinkage}} ), not favoured</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2. ( \Delta v_{\text{tot}} &gt; \Delta v_{\text{for shrinkage}} ), favoured ( \Delta v_{\text{tot}} ) tot. contraction ( t ), freeze, expand.</td>
</tr>
<tr>
<td>Macroscopic growth morphology</td>
<td>Cooling rate</td>
<td>1. Mushy zone narrow—promotes central shrinkage</td>
</tr>
<tr>
<td>Mould wall movement</td>
<td>Mould properties, casting and mould expansion</td>
<td>2. Mushy zone wide—reduces central shrinkage</td>
</tr>
</tbody>
</table>

To the mould or inward, by casting wall movement but not by direct communication with the remaining liquid. The consequence of outward expansion, as is well known with spheroidal graphite irons, increases the total volume of the mould cavity, contributing directly to the appearance of either spurious or gross shrinkage cavities in the central areas of the casting and/or to the larger size (heavier) castings, depending on the time the expansion occurs relative to the mould filling and freezing processes. Conversely, inward casting wall movement promotes casting soundness. The difference in the shrinkage behaviour between the two irons thus lies in the nature and scale of differences in their microscopic and macroscopic growth morphologies.

Whilst the primary cause for the volumetric expansion of spheroidal graphite iron castings lies in the growth of graphite, the direction and, to a lesser extent, the magnitude of this expansion is conditioned by the casting geometry. The work of Vondrak and Pribyl\(^{17,19,20}\) and other workers has demonstrated that the direction of the expansion forces due to graphite growth or due to solid contraction can be outward or inward depending on the casting geometry. In a simply shaped casting, flat and convex casting surfaces tend to expand outwards and concave surfaces inwards. The importance of rigid or strong moulds and cores for minimizing the extent of expansion of spheroidal graphite iron castings has been proven by research and demonstrated in practice.

Summary of main factors which control shrinkage cavities in spheroidal graphite iron castings.

These factors are summarised in Table 1. Symbols as in Fig. 2.

Two main conclusions can be drawn from Table 1. Firstly, the presence of shrinkage cavities in spheroidal graphite iron castings is influenced by a number of factors the separate effect of which can be qualitatively predicted. Under production conditions the combined effect of all the factors is more difficult to predict. Secondly, in principle it should be possible to produce a sound spheroidal graphite iron casting without feeders by controlling the factors in Table 1. This has been proposed previously by Reynolds et al.\(^1\) and by Loper et al.\(^2\). However, the fact that it is far more common in foundry practice to use feeders is an indication of the practical difficulties of predicting the conditions under which casting soundness can be obtained without feeders. The object of the experimental work described in the present paper was to provide more detail on the feeding and non-feeding conditions of spheroidal graphite iron sand castings.

**FEEDING**

Experimental work

The experimental programme was divided into two parts: (a) the application of feeders for spheroidal graphitic iron castings, and (b) a study of factors affecting casting soundness without feeders. In all the experiments, unless otherwise specified, the castings were made to the following analysis: C 3.8, Si 2.6, Mn 0.2, Ni 1.0, S 0.02, P 0.03, and Mg 0.006%. Melt treatment with Ni Mg booster was carried out at 1350 - 1475°C, melter blown with 0.4% of FeSi 75, and pouring temperature was maintained around 1350°C.

**Feeder design and feeder size effects on soundness**

The design of feeders involves several critical parameters, and for the purpose of the present work some of these were varied and others maintained constant. The main maintained constant included: cylindrical shape, ratio \(H:D = 1:5:1\), side feeding, blind type feeders, thick walls, and the application of an atmospheric cover. Some elements which were varied included: the feeder metal surface area ratio, or modulus, \(M_f\), the neck modulus \(M_n\), the location of the neck on the feeder. The modulus used is shown in Fig. 5. The following casts were made: thick plate \(3.7 \times 10 \times 20 \text{ cm}\), thin plate \(1.5 \times 20 \text{ cm}\), bar \(3.5 \times 3.5 \times 20 \text{ cm}\) and cylinder \(4 \times 20 \text{ cm}\). Feeder gating ratio 1:1.2:0.9 was used and the ingate was

![Fig. 5—Mould layout, thick plate casting](image-url)
duced tangentially into the feeder close to the feeder neck. Soundness was examined radiographically, by density measurement of castings cut into 3 cm long pieces, and by macroscopic examination of longitudinal half sections. For each casting, the highest density, viz., that of the end piece opposite the feeder, was taken as a standard for the porosity calculations for that casting. All the castings in this series were moulded in a silica sand, A.P.S. fineness No. 53–58, bonded with 3-75% of sodium silicate (SiO₂/Na₂O = 2:1, H₂O 50%) and air-set using 10% of a proprietary ester hardener.

In the first series the optimum value of the neck modulus \( M_n \) (defined as \( V_n/S_n \), where the cooling surfaces of the neck were used in the evaluation of \( S_n \)), was determined for various values of the feeder modulus \( M_f \). The results for the plate castings, shown in Fig. 6, indicate that there is an optimum neck size in relation to the modulus of the casting \( M_c \). In this work, this was found to be \( M_n = 0.5 - 0.6 \ M_c \).

The length of the neck was maintained constant and equalled 1.5 cm. The value of \( K_n = 0.5 = M_n/M_c \) was kept constant in all subsequent feeding experiments.

In the second series, the effect of feeder neck location on the feeder was investigated. The results showed that the soundest castings were obtained when the feeder neck was located at a distance equal to \( 1/3 \) from the feeder base. In the present work this means that \( 1/3 \) of the feeder height was

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Fig. 6—The effect of neck modulus, \( M_n \), on porosity

Fig. 7—The effect of feeder modulus on density variation in bar castings

Fig. 8—The effect of feeder modulus on porosity of castings of different shapes

- thin plate
- bar
- cylinder
- thick plate
in the drag and 2/3 in the cope part of the mould, Fig. 5. This location of the feeder neck was maintained constant in subsequent experiments.

In the third series, the effect of the feeder modulus, \( M_f \), on casting soundness was examined for plate, bar and cylinder castings. A typical example of density variation for the bar casting is shown in Fig. 7. The effect of the feeder modulus to casting modulus ratio, \( M_f/M_c = K_f \), on the soundness of all castings is shown in Fig. 8. The results obtained show that porosity increased rapidly when the value of \( K_f < 1 \), and that the optimum value of \( K_f \) increased from 1.2 for the cylinder to 1.6 for the thin plate casting.

Casting soundness without the use of feeders or when \( K_f < 1 \).

The variables examined in this series were as follows:
(a) alloy variables (carbon and silicon contents, or C.E.);
(b) pouring temperature and type of cast alloy matrix;
(c) casting design (concave and convex surfaces and gating systems);
(d) moulding materials of varying degrees of mould rigidity.

Unless otherwise specified, all the moulds in this series were made using sodium silicate sand and the standard alloy and melt treatments as used in the previous series. Whether castings were made without or with feeders, \( K_f < 1 \), is indicated in the corresponding graphs.
(a) The effect of carbon and silicon content on the porosity of unfed bar castings, gated in the middle, is shown in Fig. 9. The effect of the pouring temperature on the porosity of the same casting is shown in Fig. 10. The porosity of unfed pearlitic matrix bar castings poured into a cement mould was 1.4 as compared with 0.8% porosity in ferritic matrix castings.

**TABLE II** Porosity values of castings poured without feeders into cement moulds

<table>
<thead>
<tr>
<th>bar cross-section</th>
<th>number of ingots, square bar</th>
</tr>
</thead>
<tbody>
<tr>
<td>con- concave</td>
<td>one, one, two, four</td>
</tr>
<tr>
<td>ease</td>
<td></td>
</tr>
<tr>
<td>plane central end</td>
<td></td>
</tr>
<tr>
<td>two</td>
<td></td>
</tr>
<tr>
<td>porosity %</td>
<td>0.40 0.95 2.00 2.32 1.30 1.65 1.65</td>
</tr>
</tbody>
</table>
Comparative porosity values of concave, convex and plane surface bar castings, poured without feeders into cement moulds, are given in Table II. Porosity values of the bar castings without feeders poured using one, two or four ingates, in cement moulds, with all other factors constant, are also given in Table II.

(c) The effects on the density of the bar casting, using a feeder $K_f = 0.8$, and moulded in black green sand, furan, sodium silicate and cement sands, are shown in Fig. 11. The porosity of the same bar casting fed using feeders of different $K_f$ values is shown in Fig. 12.

The results obtained in this series show that several process variables, viz., alloy composition (C.E. %), mould rigidity, pouring temperature and gating method, all have a considerable influence on the shrinkage behaviour of spheroidal iron. Other variables examined had a smaller effect, but with no combination of process variables examined in the present work has it been possible to obtain a macroscopically sound casting without the application of feeders.

**THEORIES OF FEEDING SPHEROIDAL GRAPHITE IRON CASTINGS**

The use of feeders

The main methods reported to be widely used for feeder dimensioning in sand foundry casting practice are based on the application of two basic relations. The first is the modulus, also known as Chvorinov's rule, which states that the solidification time of a sand casting can be related to its modulus, viz., the volume surface area ratio. The second is the volumetric relation of feeding, which postulates that the volume of feeding liquid available in the feeder should be equal to or greater than the volumetric shrinkage requirement of the total amount of metal poured into the casting.

A number of different procedures have been proposed for the application of Chvorinov's principle, the simplest being that which has been elaborated in detail for practical application by Wlodawer, this can be stated in the well-known modulus relation:

$$M_f = K_f M_e$$  \hspace{1cm} (1)

The success of the application of the modulus relation in predicting accurately the required feeder dimensions depends on the particular method of evaluating the value of $M_e$ and on the reliability of the experimental factor $K_f$. Calculation of $M_e$ values is straightforward for castings of simple geometry, but for most castings of complex design, approximation methods are used for obtaining $M_e$. The factor $K_f$ is determined experimentally and its value...
depends on both, the thermal conditions (viz., temperature gradients) prevailing during feeding and the feeding characteristics of the alloy (viz., its freezing front morphology).

The volumetric condition of feeding can be expressed in its simplest form by:

\[(V_f + V_n) \cdot a_t = V_t\]  \hspace{1cm} (2)

where \(a_t\) represents the total volumetric contraction percent of the alloy and 'a' the feeding efficiency factor of the feeder, (approximately equal to the volume of the shrinkage pipe of the feeder in skin forming alloys, expressed as a percent of the total feeder volume). The value of \(a_t\) for spheroidal graphite iron, as already discussed, is not known with a high degree of accuracy whilst the value of 'a' has to be determined experimentally for various types of feeders. It appeared therefore more appropriate to the authors to make use of relation (1) for their research and to use relation (2) as a control for checking whether the feeder volume calculated by (1) also satisfied the relation (2).

The mean value of a from the published data for sand wall feeders was taken as 0.14.

The results obtained in the present work indicate two main conclusions on the question of the variation of the \(K_t\) factor for feeder calculations for spheroidal graphite iron sand castings. Firstly, the value of \(K_t\) is smaller for chunky and thicker castings, an observation confirming similar results obtained by previous investigators.55,56 Secondly, the value of \(K_n\) appears to be independent of the mould dilatation factor, as shown in Fig. 10. Both of these observations can be explained in terms of the feeding mechanisms involved.

In the former case, a thin plate casting requires a larger modulus feeder to maintain a positive temperature gradient during freezing for a casting in which, a directional solidification is more difficult to achieve. In the latter case, if the feeder satisfies the thermal conditions expressed by the relation (1) then such a feeder should be equally effective for a mildly dilating mould, provided that condition (2) is also met. A strongly dilating mould creates special feeding problems which cannot be resolved by increasing the value of \(K_n\) only. Some authors have suggested that feeder sizes need to be increased as C.E.S% decreases.56

Most of the iron used in the present work were of the eutectic and hyper-eutectic compositions for which the \(K_t\) value appears to be constant for the particular type of feeder and the feeding system used.

Another observation which emerges from the present work is that the value of the neck modulus, \(M_n\), and its coefficient \(K_n\) are critical for the correct application of equation (1) for feeder calculation. If the neck is too small, it freezes before feeding is completed, and if it is too large, the feeder will act as a heat source and will reduce the temperature gradient of the casting section adjacent to the feeder. This situation leads to the appearance of the shrinkage pipe extending from the feeder into the casting in skin freezing alloys and to spongy type of porosity under the feeder in mushy freezing alloys. The optimum value of \(K_n\) will depend on the feeder and feeder neck designs and on the materials used. For the feeding systems used in the present work the value \(K_n = 0.5 - 0.6\) was found.

Casting soundness without feeders

From Table 1, it can be concluded that the metallurgical conditions for producing sound spheroidal graphite iron castings without feeders could be expressed as follows:

\[\alpha_t + \alpha \cdot \Delta t \geq \beta_t\]  \hspace{1cm} (3)

where \(\alpha\) represents the liquid volumetric contraction coefficient, \(\Delta t\), the superheat temperature of the alloy in the mould, \(\alpha\) the freezing contraction and \(\beta\), the volumetric expansion during freezing. In other words, if the total contraction in the mould is balanced by the expansion during freezing due to graphite growth, a sound casting should result without feeders. If the casting is not sound even though condition (3) has been met, then two factors could have intervened. Either the mould could have failed thus creating a larger volume than could be balanced by the freezing expansion, or the freezing process could have been non-uniform so the expansion in one section of the casting was not able to compensate for the contraction in another. The production of sound spheroidal graphite iron castings without feeders rests therefore on the interaction amongst: (a) alloy behaviour, (b) mould rigidity and (c) casting and mould design variables.

Alloy behaviour. It follows from relation (3) that amount of shrinkage porosity will be reduced by increasing the volume of nodules (viz., C.E.S%) or by lowering the pouring temperature. The graphs shown in Figs. 8 and 9 provide evidence of such effects. In practice, C.E.S% control does not pose serious problems, but segregation of hyper-eutectic nodules in thick sections may create difficulties. In any alloy of a given C.E.S%, the amount of C rather than Si has a larger effect on the value of expansion, but the level of Si may control the appearance of primary carbides. The lowering of the pouring temperature is, however, limited by the danger of incomplete mould filling (loss of fluidity) as well as by the danger of appearance of primary carbides.

Growth morphology of the alloy during freezing, as discussed earlier, also influences both the type and the volume of shrinkage porosity. A combination of the effects of alloy composition, inoculation treatment and cooling conditions can lead to three distinct feeding situations as shown in Fig. 13. If the casting solidifies uniformly, Fig. 13a, liquid contraction and freezing expansion balance one another throughout the casting and a sound casting results, provided that relation (3) has been met. If the solidification proceeds by skin formation and the expansion is transmitted to the residual liquid throughout the freezing process, a sound casting would again result, Fig. 13b. On the other hand, if the freezing expansion has been transmitted to the mould instead of to the liquid, a porous casting is obtained. Such an outcome could arise through several combinations of solidification circumstances, one of which is shown in Fig. 13c. When section 1 of the casting required some feeding liquid in the early stages of freezing, Fig. 2, this liquid was supplied from section 2. In the later stages of freezing, when section 1 is expanding, it cannot return the excess liquid to section 2, owing to the location of the pasty zone and the distances involved. Instead section 1 will attempt to expand the mould. In other words, the basic metallurgical mechanisms of elimination of shrinkage porosity are provided by shrinkage compensation either in situ or by liquid flow from the expanding to the contracting section of the casting.

Mould rigidity. The mould can influence shrinkage behaviour of spheroidal graphite iron in two ways. By its rigidity it can oppose the outward casting expansion and thus promote the feeding process as discussed in the preceding paragraph. By its inward expansion, Fig. 4, it can reduce the volume of the casting cavity. This process is significant only in the early stages of freezing and, as it is
relatively small in magnitude and dependent on the casting design, it cannot be used as effectively as mould or core rigidity for controlling shrinkage behaviour of either fed or unfed spheroidal graphite iron castings.

**Design factors.** The design of the casting with its cross-section size and geometry, and the mould with its material and gating system variations, control the rate and direction of heat flow before and during freezing process. The heat transfer characteristics in turn control the feeding situations shown in Fig. 13. In addition, the heat flow processes affect mould dilation mechanisms as well as the dilation of the casting skin itself. For any given mould and casting design it could be qualitatively predicted on the basis of the factors already considered whether and how the design is likely to promote the feeding process or the opposite. Quantitatively such predictions are more difficult and in practice, neither casting nor mould designs could be readily and significantly altered. On the other hand it is often possible to vary the gating system design, mould ramming density or material and chilling and insulating applications, in order to promote casting soundness of either fed or unfed castings.

**FEEDING PRACTICE**

A practical foundryman having read the preceding account and analysis of research data may well ask two questions:

To what extent is it possible to design and calculate feeding systems for spheroidal graphite iron castings for general foundry practice?

and

When, and how, could sound spheroidal graphite iron castings be produced without the application of feeders?

It appears that the former question could be answered more readily than the latter.

**Design of feeding systems**

In general, the design of the feeding system implies resolving questions from four different groups:

(a) location, number, gating method, moulding and setting of feeders;

(b) type of feeder (top or side and blind or open in either case);

(c) auxiliary feeding aids, (feeder wall material, feeder topping material, application of atmospheric cores);

(d) feeder and feeder neck dimensions.

Although only the last of the above four groups has been considered in the present paper, it should be emphasized that in foundry practice some of the decisions from the former three groups must inevitably have a bearing on the last group.

Four different methods have been reported as being currently used for calculating feeder dimensions for spheroidal graphite iron castings in foundry practice.

(a) The thickness of the section which is being fed is used as the critical dimension and the feeder and feeder neck sizes are related to the thickness dimension by empirically-established relationships;

(b) The ratio of length plus width divided by thickness of the section, \( \frac{L + W}{T} \), is related by empirical graphs to the ratio of feeder volume to the casting volume;

(c) The effective feeder volume is related to the total volumetric contraction of the casting, viz., the volumetric condition of feeding described by the relation (2) in the present paper is applied, and

(d) The modulus method, due to Chvorinov and using the technique developed by Wlodaver, viz., relation (1) in the present paper is used.

It would seem invidious to the present authors to place the above four methods in order of merit as far as foundry practice is concerned, as all these methods are claimed to be successful by their respective users. Nevertheless it is preferred to use the last of the four methods, which, although as empirical as the other three methods, is founded on the laws of heat transfer and should therefore be generally applicable. For many castings it is an easy and simple method to apply, as illustrated by the following example of a bracket casting, Fig. 14.

The casting was moulded using sodium silicate sand, as described previously and when moulded without feeders it gave a porous casting, Fig. 15. Consequently the feeder was calculated using the modulus method.

The volume of the critical section of the bracket which controls the feeding process is:

\[ V_e = 94.8 \text{ cm}^3 \]

The cooling surface of this section is:

\[ S_e = 103 \text{ cm}^2 \]

Hence the casting modulus is:

\[ M_c = \frac{V_e}{S_e} = 0.92 \text{ cm} \]

Using the modulus relation (1):

\[ M_f = 1.2 \cdot M_c = 1.2 \cdot 0.92 = 1.1 \]

A feeder with \( h = 1.5d \) has for its modulus:

\[ M_f = \frac{1.5d}{8} \]

hence \( d = 5.9 \text{ cm} \), \( h = 8.9 \text{ cm} \).

Checking for the volumetric condition of feeding (relation 2), gives:
Fig. 15—Bracket casting made without feeder

Fig. 14—Bracket casting

\[(V_e + V_t) \alpha_t \Delta t = 14 V_t \]
\[(350 + 242) \Delta t < 14 \times 242; 2372 < 3400\]

The neck dimensions are obtained from:

\[M_n = 0.6 \times 0.6 = 0.36 \]

Selecting for the neck shape a prism with a square base and
1.5 cm long, the neck modulus becomes:

\[M_n = 0.6 \times 1.5 = 0.9\]

Using the dimensions obtained, the casting was poured at
1350°C and was macroscopically and radiographically
sound, Fig. 16. One of the authors is using the modulus
method regularly in a jobbing foundry making spheroidal
graphite iron castings from 0.5 kg to 17 tonnes.

Three complications often arise in the application of the
modulus method in foundry practice. For complex casting
shapes the value of \(M_e\) has to be obtained using various
approximation techniques. The values \(K_t\) and \(K_n\) are not
constant and particularly for light castings it is advisable
first to make a test casting with the standard \(K_t\) value. If the
feeder neck is correctly designed, the use of a larger than
optimum \(K_t\) value is not critical. The more intractable
problem is that of finding an acceptable definition of sound-
ness and agreeing on the tolerances of porosity in the
engineering industry. This is an area where future research
seem must desirable.

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Fig. 16—Bracket casting made with the feeder
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