Production of spheroidal graphite—nodular cast iron

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Commercial production of SG iron only began in Britain in the early 1950s and, by 1973, had risen to an annual level of over 405,000 tonnes, i.e. 12% of total iron castings production. However, output has declined during the current recession to a level of only 305,000 tonnes in 1977, i.e. 11% of total iron castings production. This can be accounted for mainly by a marked fall off in the production of pipe fittings and automotive castings, i.e. 326,000 tonnes in 1973; 233,000 tonnes in 1977. Production of other types of castings have remained fairly constant, despite a decline in the total production of iron castings from 3,500,000 tonnes in 1973 to only 2,800,000 tonnes in 1977.

This situation should be assessed in relation to other highly industrialised nations—Germany, 496,000 tonnes, 1973—585,000 tonnes, 1977; France, 547,000 tonnes, 1973—631,000 tonnes, 1977; Japan, 1,100,000 tonnes, 1976; USA, 2,000,000 tonnes, 1976.

It will be observed that the UK output per capita is considerably less than its major competitors. It will be appreciated that 55% of the current UK output is spun pipes and fittings, and 20% specialised automotive castings, notably crankshafts, both of which applications are by now largely developed and likely to increase only by natural growth. Therefore, this leaves only 25% in respect of all other fields of application, i.e. about 80,000 tonnes annually, a very small tonnage indeed, when related to the size of British industry. This rather slow growth rate in general engineering is not due to technical deficiencies in the producing foundries, since, from the very early days, the development of SG iron was fostered by a practical licensing system arranged by Inco, the inventors of the magnesium process. This system ensured that only suitably equipped foundries entered the field and received the necessary technical guidance. Furthermore, continued research and development over the intervening years by BCIRA, Inco, International Mecanite and many others, has resulted in many important improvements to basic production techniques, mechanical and physical properties, and ultimately the quality, reliability and competitiveness of the product. On the contrary, it is believed that the leading nations are still far behind the technical state of the art.
may be due partly to:
— a reluctance on the part of engineers to appreciate the advantages of new cast materials such as SG iron, in place of established cast steels, fabrication procedures and components machined from steel stock materials;
—and also to inadequate technical sales activity by many UK foundries.

Having briefly mentioned the current statistical position, it is now proposed to confine the remainder of this paper to matters relating to the production processes now in wide use, with the aim of stating clearly the options open to foundrymen and metallurgists with the choice depending on their particular facilities and types/grades of castings required.

HISTORICAL
Since the author was privileged to be involved with SG iron since the early days, it might be appropriate first to mention very briefly the conditions under which the material was developed up to the early 'sixties and by this means compare the situation with that we have reached today.

At the outset, most UK producers were forced to melt in existing furnaces, which included a major proportion of cold blast acid cupolas. The choice of raw materials lay between steel scrap (where electric melting was available), refined pig iron also based on steel scrap, or, blast furnace pig iron. For a long period, nickel-magnesium alloys, on which most of the early European development was based, were in short supply. This led to the development of a large number of procedures for introduction of metallic magnesium, the most important of which were the Pont a Mousson Pressure Chamber, the SKB Pressure Vessel and The Tiroler Lance Injector. Other materials used included a number of magnesium-containing alloys based on ferro-silicon. In most cases, it was necessary to heat-treat the resultant SG iron castings to obtain the necessary mechanical properties. Defects such as pinholes, non-metallic inclusions and shrinkage were rather difficult to overcome, due to relatively low pouring temperatures, high initial sulphur contents, low carbon equivalents, and lack of understanding of the importance of rigid moulds.

Nevertheless, despite these problems, the nucleus of the present market was established by these gallant early pioneers, which then formed a basis for more rapid development over the last fifteen years and it is on that period that the paper is mainly concerned.

Melting stock
The ideal base iron for subsequent magnesium treatment should be:
— high in carbon (3.5%–3.9%)
— silicon as required
— low in trace elements e.g. Ti, Pb, Sb, Bo.
— low in phosphorous < 0.5%
— low in carbide forming elements e.g. Cr, Mo, V, W, Mn.
— low in sulphur < 0.02%
— of relatively high temperature > 1450°C

The majority of producers now use one or more of the following raw materials:

1. Blast-furnace-melted low Mn. hematites are normally produced from selected ores and desulphurised to < 0.05%. Owing to the limitations imposed by the type, and large size of this melting unit, compositional control may not at times be too precise, resulting in variations of ± 0.25% silicon; phosphorus contents in excess of 0.05% and variations in the content of trace elements.
2. Electrically-melted high purity pig irons are of precise and guaranteed composition; the manganese, sulphur and trace elements likely to affect the reaction between iron and magnesium, and encourage the formation of carbides.

Typical analysis of high purity OB pig iron

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<td>Copper</td>
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<td>Nickel</td>
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3. Steel scrap. This covers a very wide range of materials of different shape and composition, arising from a variety of manufacturing processes, intended for widely varying applications. As a result, the scrap merchant, unlike the pig iron manufacturer, cannot guarantee the composition or homogeneity of his material, unless it originates from a single known source. Furthermore, even when an apparently reliable source of scrap appears to have been obtained, there is always the possibility of pieces of 'foreign' material being inadvertently mixed in a consignment.

The problem of segregation becomes even more significant when the scrap is supplied in the form of compressed bales, which form is often chosen for ease of charging and speed of melting. However, even with rapid analytical equipment, there are no simple ways of identifying the nature of scrap in the centre of a bale and such checks merely serve as a warning to the suppliers that some form of technical control is operative. The main advantage of steel scrap is its relatively low price, in relation to pig iron, though there are additional costs in respect of carbon and silicon additions. There are indications that supplies of high grade scrap may gradually decline, due to more efficient manufacturing techniques by engineers, and the increasing tendency of steel-makers to introduce minor additions of 'micro-elements', such as Cr, V, Nb, etc. As a result, important scrap merchants have recently forecast that the price differential between high grade and other types of less pure scrap will increase accordingly.

In practice, many SG iron producers tend to use a combination of two or more of these materials, so taking advantage of the lower price of scrap and the greater purity and reliability of pig iron. The effects of each of these materials and combinations thereof, will be discussed in more detail as they affect the various parts of the production process.

MELTING FURNACES AND PROCESSES
Whilst a wide variety of melting furnaces can and are used for SG iron production world wide, four main types are favoured by UK foundries:
1. Oil-fired crucible furnaces are mainly chosen by small tonnage producers, because of their relatively low capital cost and often constitute a stepping-stone on the way to more ambitious melting plant. They are simple to operate and produce metal of low sulphur content, consistent com-
they are generally limited to about 500 kg capacity and crucible life averages only 30 heats i.e. about 10 tonne metal/crucible and melting rates are rather low. Charges must consist only of high carbon pig iron and returned SG iron scrap and it is difficult to achieve tapping temperatures much in excess of 1450°C. Nevertheless this is a simple and inexpensive method of starting production of SG iron requiring at minimum of technical control and currently applied by about 12% of UK SG iron producers, even with little experience, the results obtained are very successful.

2. Oil-fired rotary furnaces in use in the UK involve a modest capital outlay, are mostly in the range 500 kg-3 tonnes capacity; melting rates are more rapid and the cost of furnace maintenance is considerably lower than with crucible furnaces. Provided the correct grade of low sulphur containing oil is used, the final sulphur content of the iron differs little from that charged. However, since melting must, for speed of operation, involve at least slightly oxidising conditions, carbon and silicon are lost in the process, the extent of which can vary in relation to oil/air ratios and pressures, melting rate, temperature of superheat and holding time within the furnace etc. Due to this situation, it is necessary to melt only high carbon pig; some firms also include a proportion of returned SG iron scrap, others utilise the SG scrap to replace pig iron in charges of grey iron, where the required carbon content is lower. There are various methods of offsetting at least part of the carbon loss; these include the addition of a low sulphur graphite, either with the cold charge, or at the 'pasty' stage; by injection, or, in more recent times in the ladle. None of these procedures are fully satisfactory, since carbon recoveries are often low and temperature losses can occur.

Replacement of silicon presents no problems, either just before tapping, or into the ladle as inoculant.

It is advisable to empty the furnace rapidly when the metal has reached the desired temperature of 1450°C-1500°C, otherwise carbon and silicon losses are accelerated and variable in degree, at a stage when adjustments to carbon content may no longer be practicable. Nevertheless, despite these problems, quite a number of SG iron producers melt in rotary furnaces, with successful results.

3. Cupolas account for the largest tonnage of SG iron produced in the UK; two large installations only melt under fully basic conditions to give an iron of high carbon and low sulphur content; three firms use 'cokeless' cupolas, developed only in the last decade and involving oil or gas firing to give irons of low sulphur and medium/high carbon content (after carbon injection into the well); most of the remainder are operated with fairly conventional acid conditions to give medium/high carbon and high sulphur contents in range 0.7%-0.9%.

The two large basic cupolas are all that remain of the original fifteen installations of various sizes. It is generally agreed that, under UK conditions, basic operation is best confined to large units of perhaps 10 tonnes per hour upwards and with continuous melting conditions. Water cooling of the melting zone is essential, otherwise refractory costs become prohibitive and very close control of melting conditions, slag ratios etc. is technically complicated.

On the contrary, the conventional acid lined cupola, which is most widely used, is simple to operate and normally delivers metal of predictable composition with minimal technical control, at reasonable cost. Furthermore, cupolas are capable of improvement with modest capital outlay, by such means as introduction of oxygen into the tuyeres, blast main or well; also by installation of two blast mains and sets of tuyeres and many SG iron producers have carried out such modifications to existing or new furnaces. By this means they regularly achieve tapping temperatures in excess of 1500°C, in association with medium/high carbon contents, with only modest increase or even similar coke charges. Metal charges normally consist of high purity pig iron, along with varying proportions of selected steel scrap, depending on the grade of SG iron required and whether heat-treatment is subsequently applied.

The main disadvantage of cupolas is the high sulphur content of the tapped iron. For most purposes, and on the grounds of economy, this should be reduced to 0.02% or lower, otherwise an excessive addition of magnesium will be required. A number of procedures are now in regular use for this purpose, notably:

- the porous plug ladle
- the shaking-ladle
- both involving the additions of calcium carbide;
- direct addition of sodium-carbonate (soda ash).

Calcium carbide added to metal at temperatures of 1500°C and above gives rapid sulphur removal to as low as 0.05%, S, with temperature loss in the range 50/100°C; the cost of a 'shaking-ladle' installation is high and occupies a relatively large floor area; the porous plug system can, if required, be adapted quite cheaply to existing ladles and utilise dry air or nitrogen to give the necessary stirring action. However, disposal of the resultant carbide slag is subject to increasingly strict control and this has led to tests with burnt lime and fluorspar, which are very encouraging in respect of sulphur levels and appear to overcome the slag problem. Sodium carbonate can be added during tapping into a normal foundry ladle; if the metal temperature is 1450°C and over, sulphur levels of 0.02-0.03% are regularly obtained. However, the liquid slag so produced is rather difficult to remove and the process is 'heavy' on ladle lining material.

4. Induction melting has been increasingly adopted by small medium SG iron foundries during the last fifteen years and this move has been accelerated in more recent times by anti-pollution regulations, heavily weighted against the cupolas, and by the incentive of local and national government grants made to foundries for installation of new capital equipment.

At present, over sixty firms have available electric induction furnaces, which are used to melt all or part of their SG iron production, or to superheat and condition such metal previously melted in other types of furnaces. The 'coreless' induction furnace is mainly preferred due to its simplicity of operation, a desirable feature for foundries with a tradition of electric melting; the even balance of electricity requirement, the close control of composition and temperature, which is easily obtained with minimum attention. Broadly speaking, melting losses are negligible and charges may consist of various proportions of pig iron, steel scrap and even clean machining stock from SG iron castings. Carburisation, particularly in 50 cycle mains frequency furnaces, is both rapid and predictable. Sizes in present use for SG iron production range from as little as 150 kg to as large as 30 tonnes capacity; the small units are generally operated at medium/high frequency; from 500 kg-2 tonnes, the 'triple' frequency type is often favoured; from 2 tonnes onwards the mains frequency type is widely used.

The disadvantages of induction furnaces include:

- high initial capital outlay
- limitations in size and shape of raw materials
- raw materials should be relatively dry if a liquid bath is being maintained, otherwise splashing does occur
- reasonably clean raw materials are essential to avoid; an excessive volume of slag, which is difficult to remove and can locally increase or decrease lining thickness and cause atmospheric pollution from volatile contaminants such as...
cutting fluids, surface coatings etc.
—lining life can be variable and somewhat unpredictable,
and the consequence of a local failure may prove very
expensive.

—the complicated and seasonably affected electricity tariffs,
which are particularly onerous during winter periods, and
which tend to favour off peak melting at premium wage
rates.

Nevertheless, since the advantages outweigh the dis
advantages, induction melting is here to stay, and will, in the
near future, be responsible for the majority of tonnage of SG
iron produced in foundries delivering say 500/5000 tonnes
of castings annually.

DULEXING

Before leaving the subject of melting, it is necessary to dis-
cuss briefly the process known as ‘duplexing’, which has
been adopted for some years by the larger foundries and
become more widely used, as the output of SG iron
increases.

Furnaces used for duplexing are usually of the channel or
coreless induction type, of large capacity, with low electrical
input and have a number of functions:

—to replace the loss in temperature of cupola metal, which
has occurred due to desulphurisation and carburation in a
porous plug or shaking ladle,

to level out any variations in composition that have
occurred during cupola melting and so reduce the need
for analytical control to an absolute minimum.

to serve as a reservoir of metal, with the aim of taking
care of variations in demand from a mechanised moulding
line; or as a means of collection of a large quantity of
metal of precise composition for pouring a single heavy
casting.

to ensure maximum utilisation of induction furnaces used
as prime melters.

MAGNESIUM TREATMENT

Since commercial production of SG iron commenced, a very
large number of procedures have been developed for intro-
duction of the required 0.93%/0.05% magnesium. Some
are still in use and many others have been discarded in
favour of others of a more flexible nature. Sufficient to re-
cord that, at present, most European producers make use of:
alloys based on ferro-silicon; nickel magnesium; metallic
magnesium introduced in a vessel developed by Georg
Fischer and, therefore, it is proposed to confine most of this
section to these materials.

NICKEL MAGNESIUM ALLOYS

The traditional nickel magnesium alloys (Ni:85% Mg:15%)
have survived the periods of nickel shortage, which tended to
limit their use and to open the gates to new procedures,
which were usually less expensive, but involved the installa-
tion of special equipment. Furthermore, additional nickel
magnesium alloys of different nickel and magnesium content
have subsequently been developed, with improved perfor-
mance and better environmental conditions. Neverthe-
less, due to the relatively high initial cost of these alloys,
their use is now mainly confined to those firms such as roll-
makers and producers of austenitic irons, where the nickel
increment is particularly beneficial and to small producers
of SG iron, not prepared to install the facilities necessary to
introduce and control the less expensive alloys or metallic
magnesium.

Since nickel-magnesium alloy is a dense material, it can
simply be placed on the bottom of a ladle of virtually any
size and shape, and iron, even of high sulphur content

(0.8%/0.1%), tapped on top without special preparation. If
required, it is also practicable to make the addition to the
surface of an already filled ladle, in the case of small unit
quantities. Recovery of magnesium is high (50%/75%) and
predictable, and is not as sensitive to metal temperature as
are the nickel-free procedures. However, for a given sulphur
content and metal temperature, the cost of treatment with
nickel magnesiun is at least twice that of ferro silicon
magnesiun, and many times greater than with metallic
magnesiun.

FERRO SILICON MAGNESIUM ALLOYS

The majority of UK SG iron producers now make use of
ferro silicon magnesium alloys, which basically contain
3%/6% magnesium; 40%/50% silicon and small propor-
tions of trace elements, such as calcium and aluminium,
which vary in content according to the source of the alloy.
These trace elements influence magnesium recovery,
imoculating characteristics, and the tendency to form casting
defects such as pinholing, dross etc. Some suppliers have
deliberately introduced other trace elements such as barium,
rare earths, lanthanum and offer different levels of calcium.
Various claims are made concerning the benefits that thereby
accrete. Furthermore, the sizing of these alloys can vary from
<1 mm to lumps of 20/40 mm, and it is important to choose
the size and trace element content most suitable for the
particular method of addition. Since the ferro silicon
magnesiun alloys are of relatively low density, they must be
prevented from floating to the surface of the liquid iron
during the time the ladle is filling, otherwise a high propor-
tion of the magnesium will be lost. This is usually accom-
plished by a well tried process, known as the Sandwich
Technique (Fig. 1), which means the alloy is housed in a
recess in the bottom of ladle and covered with light steel
punchings, or an SG iron, or steel plate. For optimum
magnesiun recovery, the lined height of the ladle should
preferably be 1/2 times the lined inside diameter. This
procedure prevents premature flotation of the alloy and the reaction is normally delayed by 3/5 seconds from commencement of tapping, by which time, the ladle is at least 1/3 full of liquid metal. At a temperature of 1500°C, in a deep ladle, magnesium recovery is normally 45%/50% i.e. an iron with sulphur content of around 0.015% would require an addition of 2.0%/2.3% of 5% Mg. Fe. Si. alloy.

In the case of high sulphur irons, tapped directly from acid cupolas, only a few firms apply the ‘Sandwich Technique’, since a large addition of 3.0%/4.0% of ferro silicon magnesium alloy is required, involving a high silicon increment and loss of temperature. A number of alternative procedures have been developed to take care of this problem, the common factors being, hot metal (1500°C and above), desulphurisation and magnesium treatment within a porous plug ladle.

"OSMOS" PROCESS

A stream of nitrogen or dry compressed air is introduced through a ‘porous’ brick fitted into the bottom of the ladle, which produces a vigorous stirring action, and so ensures that an addition of 1.5%/2.0% calcium carbide, or 3.0%/4.0% burnt lime is intimately mixed with the liquid metal to reduce the sulphur content to 0.015% and below. Subsequently, fine magnesium ferro silicon alloy is fed through a funnel on to a clean part of the metal surface and solution assisted by the stirring action from the nitrogen or compressed air. (Fig. 2)

![Diagram of Osmos Process]

"TRIGGER" PROCESS

Prior to filling, the alloy can be placed in recess in the bottom of the porous plug ladle, as with the 'Sandwich Process', and covered with a mixture of calcium carbide and graphite, which forms a hard protective crust due to fusion from the heat of the first metal. When desulphurisation is complete, the crust is pierced by a sharp metal bar and the reaction with magnesium allowed to take place.

![Diagram of Trigger Process]

Both these procedures were developed originally by the International Mechanite Metal Company, and successfully applied by a large number of firms with cupola melting only, providing that the temperature of the tapped metal is high enough to compensate for a loss of around 100°C.

PLUNGING PROCESS

Low density alloys based on ferro silicon are frequently plunged and held below the metal surface by many West European foundries, particularly in Germany, though this practice has not found lasting favour in Britain. As with the 'Sandwich Technique' a deep ladle is most effective, the ratio of height to diameter being approximately 2:1. The plunger, is normally shaped like a deep cup, the refractory being strengthened by steel mesh and a coating applied to the surface, and the whole assembly thoroughly dried before use. A number of holes are incorporated to allow entry of metal and escape of magnesium. Alternatively, some firms make use of graphite based crucibles, and others an SG iron casting heavily blacked before each treatment, though the life of this type of plunger is considerably shorter than the first two. In most cases, the plunger and ladle lid are attached to a pneumatic cylinder and the whole assembly located behind a protective shield with the control lever outside. (Fig. 3)

The alloy VL55, developed by Metallgesellschaft A.G., containing 30% Mg, 5% Ca, 30% Si, remainder Fe, is widely used. It is available in lump form, in which case, the required quantity is introduced into the plunger in a thin steel can, or pre-cast by the manufacturers into a steel can with the weight of addition recorded on the outside. The reaction is relatively violent due to the high magnesium content, but magnesium recoveries are high and consistent due
to the precise method of addition and the high calcium content. The required addition varies from as low as 0-3% for very low sulphur irons to 0-8% for high sulphur irons direct from the cupola.

Conventional ferro silicon magnesium alloys and even metallic magnesium or ‘Elektron’ turnings are also introduced by plunging, with high consistent magnesium recovery.

The disadvantages of this procedure are:
--- the cost of the plungers and pneumatic equipment
--- the temperature loss involved in heating the plunger
--- the necessity of relarding before pouring, with further temperature loss.

**METALLIC MAGNESIUM**

During the last twenty years, a large number of processes have been developed for introduction of metallic magnesium, but with a few exceptions, they have since been discarded in favour of more simple procedures involving ferro silicon magnesium alloys. However, the most notable exception is the converter, developed by Georg Fischer—Switzerland, which is now well established by a number of large SG iron producers and is likely to become more widely accepted as the production of SG iron increases.

Georg Fischer claim that the converter enables foundries to introduce pure magnesium, in the form of ingot, into liquid iron with a wide range of sulphur contents, safely and efficiently, and by so doing, produce SG iron consistently, and in large volume. As far as the author is aware, only three UK producers regularly use this process at present, though a number of other firms have been involved in trials. Briefly, the magnesium is housed in a chamber which is fitted with a perforated refractory wall, and attached to the side of the converter; the metal is introduced with the converter in the horizontal position, the magnesium being uppermost; the entry is sealed pneumatically; the vessel is then rotated into the vertical position to permit metal to enter the chamber and so allow the magnesium to dissolve in the iron. After the reaction is complete, the lid is opened and the liquid SG is decanted over a slag notch into the pouring ladle. It is reported that the process is very cheap to operate, though the initial cost of equipment is high and also involves royalty payments. Furthermore, UK experience suggests that it may prove difficult to adapt the process in an existing building to melting and moulding plant laid out for other purposes.

The best results are obtained when the converter is operated continuously with consistently hot metal but problems may occur when the converter is allowed to cool down, due to a breakdown in supply of metal or moulds.

A small number of foundries are using coke, impregnated with approximately 40% magnesium (‘Magcoker’ developed by Foseco International). Some firms apply a plunging technique similar to that earlier described for VL55 alloy, and others use a more recently developed rotary ladle; which is on the lines of the Fischer converter, but fitted for operation by a simple handwheel. As with the Fischer converter, it is claimed that the process can be used with iron of widely varying sulphur content and that the ‘rotary ladle’ is particularly useful to those firms with acid cupolas and who require relatively small unit quantities. Up to present time, experience in the UK is limited to a few trials. (Fig. 4).

To summarise, there are a wide range of alloys and procedures for introduction of magnesium into iron, the choice depending on the needs of the particular foundry. Direct addition costs for treatment of low sulphur irons can vary from as little as £300 per tonne for metallic magnesium to as high as £20.00 per tonne for nickel based magnesium alloys. However, to achieve the lowest cost of addition would necessitate considerable capital expenditure, whereas to use ferro silicon magnesium or nickel magnesium alloys, requires little or no capital expenditure. Obviously, if output is small a large capital outlay would not be justified, and Ni. Mg. or Fe. Si. Mag. are best used, whereas, if annual output is say 5000 tonnes upwards, serious considerations should be given to the use of metallic magnesium.

Before leaving the subject of treatment, it should be appreciated that most of the magnesium containing alloys are available with or without mischmetal (0-25%-0-5%). If it is considered that there is a danger of small amounts of trace elements being present in the raw materials (particularly in steel scrap) then the mischmetal containing variety should be used (otherwise graphite form can be impaired).

However, if high purity pig, such as O.B. iron, is used then the straight magnesium containing alloy is adequate. When use is made of metallic magnesium or Magcoker then a separate mischmetal addition should be made after magnesium treatment, by plunging the mischmetal, attached to a steel rod, below the cleaned metal surface.

**INOCULATION**

Whether the end requirement is an SG iron with pearlitic or ferritic matrix, it is essential (except in the case of metal working rolls or other specialised applications), to avoid the presence of brittle ‘as-cast’ carbides. This can be accomplished by post inoculation, which normally takes the form of an addition, preferably after magnesium treatment, of 3/6 mm sized 75%/80% ferro silicon.

The precise amount of silicon introduced depends on the type of magnesium addition and the section thickness of the casting etc. and varies between 0.3-1.0%. Naturally, the silicon content of the furnace charge should be calculated to take account of the silicon increment from the magnesium alloy and inoculant to give a final silicon, which is normally in the range 2.3%-3.0%.

If ferro silicons are to be effective as inoculants (rather than furnace additions), they should contain a small proportion of such trace elements as aluminium (1-0%/1.5%), zirconium (7%/1.0%), barium, calcium, certain rare earths etc. and before making a choice, a precise analysis of such elements should be obtained from the supplier and the material checked at regular intervals to determine its consistency.

The inoculation effect of ferro silicon starts to ‘fade’ soon after the addition has been made and if ‘as-cast’ carbides are to be avoided in relatively thin sections, the inoculant should
be added immediately prior to pouring the first mould and the total pouring time limited to as short a duration as possible (preferably less than ten minutes).

If the casting design is such that the surface area to volume is large, or very thin sections are involved, it may not be possible to avoid 'as-cast' carbides, even with good ladle inoculation practice. In these cases, it may be desirable to make a late supplementary inoculation within the mould itself or during reladdling. This may involve a very small addition of inoculant (0.1%) positioned in the head box, or gating system, or, indeed, made to the metal stream during pouring, or, if reladdling, in the actual pouring ladle. A number of proprietary materials based on ferro silicon are marketed for this purpose; one of these is known as 'Germalloy' (4% Al, Fe, Si,) is available in as-cast shapes of various weights; another is in the form of fine particles in pre-weighed quantities in 'tea-bags'. Each of the materials has its supporters, the main point being when and how the addition is made, rather than how the form or quantity of the ferro silicon is given. Preferably, the mould inoculant should start to dissolve when pouring commences, with solution complete only when the mould is filled. If so, results are excellent, with very high nodule counts and correspondingly high 'as-cast' ductility. The main problem is ensuring that every mould does indeed contain the inoculant, which may involve extra supervision, before the moulds are closed, if the inoculant is positioned in the gating system. Ideally, the inoculant should be located in a stoppered runner bush, but this is normally possible only with larger moulds and as such is easily visible from the outside. (Fig. 5).

Very recently, special equipment has been designed for introduction of fine grained inoculant to the stream of metal during actual pouring. The electrical control apparatus involved is reported to ensure that the inoculant starts feeding into the metal stream simultaneously as the ladle is tilted and ceases precisely as the mould is filled. Such equipment is now in use in a few German foundries and its development will no doubt extend to other countries in due course.

To summarise, it should be appreciated that inoculation is a vital step in the production of SG iron castings and should be carried out with the same care and attention to detail normally afforded to magnesium treatment, if the best results are to be consistently obtained.

**MOULDING, GATING, FEEDING, ETC.**

Virtually all the moulding and coremaking procedures applying to grey iron are also used to produce SG iron castings, these including green sand; cold set procedures, shell-moulding, cement and permanent metal moulds. However, since the expansion that occurs during the formation of spheroidal graphite is greater than with flake graphite and the proportion of graphite greater, due to the higher carbon content of SG iron, it is even more important to pay special attention to mould and core rigidity. If this is done, then sound castings can be obtained with minimum of feeding and high casting yields (50%–80%); if not, the mould wall deformation may occur, particularly in heavy sections, and, unless adequate feeding is carried out, this will be associated with shrinkage defects. Some firms have adopted the use of very rigid moulds and cores to produce certain types of medium-heavy SG iron castings with little or no feeding. The main provisos are that the sections should be fairly even; use made of strong rigid moulding boxes; the mould filled rapidly and evenly to facilitate homogeneous temperature conditions in all parts; the carbon equivalent should be approximately of eutectic composition. Castings weighing from a few hundred kilos to twenty tonnes have been produced successfully by this so-called 'Riserless Mould' technique.

Special attention should be paid to the choice of mould and core coatings; additions introduced in green sand practice to improve casting surface finish; accelerators used

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**Fig. 5—Some methods of mould inoculation**
in 'cold set' processes. Certain of these materials have the disadvantage of releasing sulphur containing compounds into the liquid iron, and by so doing create a relatively thin layer of flake graphite on the surface.

In many instances this may go unnoticed, especially if the casting has a liberal machining allowance. However, once observed, steps should be taken to overcome the problem, by more careful selection of moulding materials, rather than by raising the overall magnesium content, which will create other problems.

Gating systems should be designed to ensure that moulds are filled as rapidly and smoothly as possible. Since magnesium is a 'dross' forming element (Mg, O, Mg S, Mg Si, O₂ etc.), the height of the runner bar should be about twice its width. A suitable choke should be built into the system, to ensure that any non-metal inclusions float above the metal stream and are retained in the runner.

A simple system found to be effective in many applications, involves an overlap in the runner bar (Fig. 6) which serves as a choke and the area of which can be altered quite simply, to suit a variety of casting weights and sizes. In some instances, firms find it useful to incorporate a strainer core in the downsprue and with larger castings stopped head boxes are to be recommended. As a general observation, it is good practice to design the running system separately from the feeding system, even though the two are often linked together in practice, through a side feeder.

As in steel founding, blind side feeders are more effective when incorporating a V notch or pencil core on the top side, to utilise atmospheric pressure for as long as possible.

Alternatively, when open side feeders are used, these should be topped with a thick layer of exothermic material for effective feeding. When side feeders are considered necessary to ensure a sound casting, then the metal should enter the casting by this means, to ensure directional solidification. Should this not be possible, by virtue of the geometry of the casting, then the side riser should be isolated to avoid the heat losses.

Top risers are sometimes unavoidable and, in this case, the riser should incorporate exothermic or insulating sleeves and be positioned well clear of the casting surface, to avoid under riser shrinkage. As a rough guide, the feeding distance either side of a feeder head, or correctly designed riser, is approximately ten times the thickness of the section being fed.

A common error is the impression that it is 'playing safe' to position a large number of relatively small diameter heads on or around the casting, with the result that 'under riser shrinkage' often occurs, with different risers being so affected in successive pours, due to changes in the heat pattern within the casting. In practice, a smaller number of properly calculated larger risers (feeders), positioned at the full feeding distance from each other, are more effective.

Whilst these simple observations will be of assistance in design and positioning of feeders (risers), each casting must of course be assessed individually, according to its geometry, volume/surface area ratio.

In some instances cast iron, silicon carbide, graphite denseners or 'chromite sand' are a necessity to supplement normal feeding, by adjusting an adverse thermal gradient, particularly in respect of isolated bosses or heavy local sections.

Finally, whilst the function of running and feeding systems is to ensure that clean sound castings are obtained, it is also important, when designing such systems, to consider that they have to be removed from the casting, with as little expense as possible.

This is a particularly important consideration when use is made of O.B. high purity pig iron, for by such means, the SG iron casting is fully ductile in the 'as-cast' condition. It is a simple matter to design non-feeding ingates to break off, on, or near the casting; somewhat more difficult in respect of side feeders, where the size of the gate area is controlled by the need to ensure adequate feeding; very difficult, where top risers are used. However, with care, the ingate geometry can often be arranged to allow break-off to occur fairly near to the casting and by so doing minimise the need for expensive cut-off wheels. For instance, a local notch, perhaps 10/15 mm away from the casting, or some other form of constriction in the ingate, is often effective for knocking off a side feeder, thus leaving a small stub on the casting for removal with minimum grinding. 'Washburn' knock off cores may be applied for top risers, though these are much more widely used in steel casting production.

POURING, COOLING ETC.

A layer of slag is formed during magnesium treatment and this should be thoroughly removed before pouring commences by use of a slag coagulant. However, as an additional safeguard, it is also advisable to use a 'tea-pot' spout ladle and where possible 'stoppered' moulds.

The white magnesium oxide fume formed during treatment is completely harmless, indeed magnesium oxide constitutes an important aid to overcoming certain digestive disorders! However, such fume, if allowed to escape to atmosphere, does reduce vision in the foundry and if possible should be avoided. This can be accomplished simply and cheaply by use of a 'tundish-cover' designed by BCIRA. This consists of a circular steel cover on which is welded a loosely fitting skirt of thin sheet steel. An oblong shaped bush or 'tundish' is welded to the top side of the cover and a hole cut through the cover to allow entry of the metal. The tundish is lined with 'cold set' sand and blacked, and the underside of the cover lined with ganister, or some other suitable refractory. (Fig. 7)

It is advisable to fit two 'eye-bolts' on to the top of the
cover for handling purposes. The cover should be positioned, so that the metal enters the ladle without impinging on to the magnesium alloy.

The metal is tapped into the ‘tundish’, it then passes down into the ladle and the magnesium oxide fumes condense on to the inside of the cover and are so prevented entering the shop atmosphere. This simple procedure is completely effective, and will certainly become widely adopted.

If heat treatment is to be avoided, it is important to regulate the cooling rate of castings after solidification. For example, if the ferritic grades are required, the temperature of the castings should be allowed to fall below 700°C before knockout. Obviously the precise time involved relates to the mass and weight of the particular castings and can be assessed by observing the colour.

HEAT-TREATMENT

The ‘as-cast’ microstructure of SG iron produced from relatively impure raw materials, such as steel scrap, is normally pearlitic and in many instances also contains a proportion of primary carbide. If such material is to consistently meet the requirements of BSS 2789, then it is necessary to apply some form of heat treatment; the most widely used procedures are:

1. A full annealing cycle—this involves holding 2–6 hours at 900°C; then either, cool to 700°C and hold for 4–12 hours, or cool slowly through the critical range 800°C–700°C. The furnace temperature should be allowed to fall below 600°C before the castings are removed. Annealing is applied to meet BSS 2789 grades—370/17 420/12.

2. Normalising involves holding at 900°C for 2–6 hours and cooling in air from 850°C. This applied to meet the BSS 2789 pearlitic grades—600/3 700/2 800/2.

3. A semi anneal involves holding 2–6 hours at 900°C followed by cooling in air from 750°C–800°C. This is applied to meet BSS 2789 pearlitic/ferritic grade—500/7.

Where high through hardness, or a narrow range of pearlitic hardness is specified by the customer, an oil quench and temper can be applied. High surface hardness can be obtained by flame or induction hardening SG iron with an initially pearlitic matrix. In some applications a stress relief treatment is applied by holding in the temperature range 500°C/600°C.

The main advantage of heat treatment is that, by this means, it is possible to achieve most grades specified in the BSS 2789 from the same basic metal composition. This is an advantage to those foundries who regularly produce a wide range of SG iron castings in grades from ferritic to fully pearlitic and are unable to segregate the moulds according to particular metal requirements.

However, heat treatment also has a number of disadvantages. These include:

—The high capital cost of the furnaces, which might be better employed in productive equipment.

—The cost of labour necessary to service and to transport the castings, to and from the furnaces.

—The ever increasing cost of fuel.

—The cost of removing surface oxide scale, which is usually formed during heat-treatment (unless inert atmospheres are applied). Furthermore, in certain casting designs, oxide scale can occur in relatively inaccessible critical areas, such as oil-ways and if this is not removed, may cause failures in service.

—Distortion may occur, which, at the best, can be corrected by expensive and time consuming straightening operations. Furthermore, dimensional variations can also occur as a result of different levels of expansion during heat treatment. Such growth is related to the initial microstructure of the castings, which itself can vary according to the quality of the raw materials and the geometry of the casting.

—Operations such as heat treatment, extra shot blasting to remove oxide scale—straightening etc. and the extra handling of the castings to and from the location of the various equipment, is obviously time consuming. This has the effect of tying up capital, with an adverse effect on ‘cash-flow’ and could, on occasions, affect customer relations if deliveries are delayed.

‘AS-CAST’ OR HEAT-TREATMENT?

Fortunately, during the last decade, the ready availability of high-purity pig, such as OB iron has, in most instances alleviated the necessity for heat treatment, with the result that foundries who commenced production of SG iron since the mid ‘sixties have been able to do so, more on the flow lines of grey iron, than steel casting production.

Ferritic grades can be readily achieved in the ‘as-cast’ condition, by direct melting of charges consisting of high
purity pig iron and returned scrap, though in many cases it is also practicable to reduce metal costs by including a proportion of carefully selected steel scrap. Where pearlitic or pearlitic/ferritic grades are required, these can best be obtained ‘as-cast’, either by alloying with small proportions of copper or tin, or by raising the proportion of steel scrap in the charge.

The choice will depend on the proportion of the various grades required e.g. if, in many cases, the main demand is for the ductile ferritic grades, then it is more convenient to produce the occasional pearlitic or pearlitic/ferritic grades by ladle addition of the aforementioned alloying elements; if, however, the demand for different grades is more evenly balanced, it is often more economical to vary the proportion of pig iron and steel scrap in the furnace charge.

Apart from the obvious benefits of avoiding heat treatment, the ‘as-cast’ process can provide other advantages, not so readily assessed in financial terms. These include:

- Reduced storage and handling due to greater density of pig iron.
- Consistency of incoming material.
- Better furnace utilisation, with less energy consumption.
- Reduction in furnace additions.
- Reduced addition of magnesium alloys.
- Higher casting yield— with rigid moulds.
- Reduced overall handling due to less operations.

The most significant argument in favour of steel scrap is that it can be purchased for approximately 50% of the price of pig iron. However, there are indications that this large price differential may be reduced in the next few years and that the quantity of high quality steel scrap available for SG iron production may be less, with obvious effects on the price level. Furthermore, the cost of necessary additions particularly carbon and ferro-silicon is increasing.

Naturally, when comparing the overall cost of the two procedures, the needs and equipment of individual foundries must play a large part in the final choice. For instance, some foundries are well equipped with heat treatment furnace capacity and also with analytical equipment for rapid checks of liquid metal; whereas other firms would need to use the services of specialist heat treatment firms or to invest capital in new furnaces.

In general terms it is true to say that the cost of good quality steel scrap and ‘outside’ heat treatment is equivalent or slightly more than the cost of high purity pig, and the other advantages of the ‘as-cast’ process, take the form of a ‘bonus’ in respect of cost saving and/or quality.

QUALITY CONTROL

It is generally accepted that a large part of the technical control necessary to ensure that only metallurgically acceptable SG iron castings are despatched, should be carried out, during production on the foundry floor, rather than ‘after the event’ in a laboratory. In this case, the first priority is to ensure that the graphite structure is fully spheroidal before the moulds lose their ladle identity. This can be achieved by rapid micro-examination of a small sample or in a ‘Sonic’ testing unit developed by BCIRA, involving a ‘Lynchiugh’ round test bar, either of which samples should be cast towards the end of each ladle. In a reasonably well organised foundry, either of these tests should provide the necessary information in less than twenty minutes, i.e., before the moulds are knocked out.

The castings can then be released for cleaning, settling (heat treatment, if applicable), or if the tests indicate an incorrect graphite structure, segregated for confirmatory checks on additional samples from individual castings. In the final inspection stage, the matrix structure can be determined by micro-examination of cast on samples, or by rapid hardness checks at predetermined locations on the casting. Unlike flake graphite irons, it is possible to assess, with reasonable accuracy, the mechanical properties of SG iron from the microstructure, though test bars cast, according to the designs recommended in BSS 2789, are often used for confirmation and/or for the benefit of those customers who require such information.

In order to achieve the desired results consistently, it is advisable to apply a simple control procedure at certain key points.

1. Weighing. All raw materials and additions should be accurately weighed. For instance, it is not good practice to estimate the weight of metal by its height in the ladle, since this can vary according to lining thickness etc.

2. Incoming melting stock. Since OB pig irons specially produced for SG iron production are of guaranteed analysis, analytical checks are not necessary. However, some form of examination is essential in the case of heterogeneous materials such as steel scrap, if only as a tentative control over the merchant. Visual examination is always applied, and some of the larger firms with spectrographic equipment, carry out rapid ‘spot-check’ analyses, particularly for such elements as chromium, rather as a deterrent, than as a source of positive information.

3. Melting. The carbon equivalent is normally determined before each tap, in the case of electric furnaces, and periodically in respect of cupolas. Those firms with rapid spectrographic equipment analyse the bath for major and tramp elements, particularly if steel-based charges are used.

4. Magnesium treatment. Since it is essential to ensure a consistent residual magnesium content, the temperature and weight of metal must be known.

5. Metallography. As previously stated a small sample poured towards the end of the ladle should be roughly polished, sufficient to be sure that the graphite is spheroidal. It is intended to deal only with those defects peculiar to SG iron or to which SG iron is more prone than grey iron.

DEFECTS

(a) Shrinkage. It is generally accepted that SG iron castings produced in non-rigid moulds e.g. green sand (100 p.s.i.), unbacked shell moulds etc. are more prone to shrinkage than grey iron castings of a similar design, produced in a similar manner. This appears to be due to the greater degree of expansion, which occurs during the formation of spheroidal graphite, which causes a higher level of mould wall deformation. However, when rigid moulds, bonded with cement, cold set resins etc. are used, the high expansion, characteristics of spheroidal graphite formation, can be fully utilised to reduce the incidence of shrinkage. In many instances this has led to medium/heavy castings of relatively even section being produced sound, with little or no feeding and casting yields up to 80%.

Obviously, it may not be practicable to use rigid moulds for repetitive production of relatively light castings and for such applications green sand practice will continue to be applied. However, there is an increasing move away from conventional pneumatic moulding machines to high pressure hydraulic units, which give more consistently rigid moulds of high hardness, even on vertical walls and operate with very low moisture content. Some firms report that such changes have resulted in sounder and lighter SG iron castings and an overall improvement in casting yield of 5-10%.

As a further aid to avoiding shrinkage defects, the carbon equivalent should be maintained at, or slightly above, eutectic level i.e. 4.3–4.5 depending on the section and mass
of the casting. It is essential to avoid the presence of primary carbides, and this can be accomplished by avoiding excessive superheating, particularly of electric furnace melted metal, careful attention to the inoculation stage and by avoiding high residual magnesium contents.

(b) Non-metallic inclusions. Defects of this type, commonly termed 'dross', normally consist of magnesium compounds including oxide, silicate and sulphide and generally occur on the cope side of the casting or under cores. Dross can occur due to:

- excess magnesium content i.e. <0.5%, therefore, magnesium should be retained as low as possible, conducive with obtaining fully spheroidal graphite throughout the pouring cycle.
- high initial sulphur content, low sulphur melting stock should be used and if sulphur pick up occurs during melting, then desulphurisation should be applied.
- low pouring temperature — unless very heavy castings are involved, the preferred temperature range is 1350°-1450°C.
- turbulent pouring due to incorrectly designed running system etc. It is always advisable to pour fast and smooth.
- dirty ladle linings.

(c) Pinholing. This is a small hydrogen gas hole, which occurs just under the skin of the casting and is of very little depth. Pinholes generally occur in groups and are often observed after the surface oxide scale from heat treatment has been removed by shot blasting. They are more unsightly than dangerous, since a single machining operation is normally sufficient for their removal. However, if seen, they do cause rejections and the reasons for their occurrence are often similar to those that cause dross, indeed, the two defects are often associated. It is not intended to deal with all the causes, since there are very many. Sufficient to say that aluminium arising from additions of magnesium ferro silicon alloys, and most types of inoculants, appears to act as a 'catalyst', to other unsatisfactory conditions and, therefore, the aluminium content is best retained at <0.15%. Furthermore, should an epidemic of pinholing occur, it often helps to:

- raise the pouring temperature
- reduce the moisture content of the sand
- increase the effective volatile content of the sand.

However, if the defect occurs only to a limited extent in individual castings it may be due to:
- slow pouring.
- turbulent pouring i.e. where two streams of metal meet.
- location of the running system etc.

SPECIAL ALLOYS, HEAVY CASTINGS, ETC.

The information in this paper refers only to SG iron castings of moderate section and weight and it is important to appreciate that other factors must be taken into account and dealt with accordingly, when producing very heavy thick-sectioned castings, which solidify much more slowly. In particular, the basic metallurgy must be modified and mould inoculation is essential if undesirable graphite forms, carbon flotation and grain boundary carbides are to be avoided.

Likewise, other considerations must be taken into account, when producing the range of high nickel austenitic irons known as 'Ni Resists'. Highly ductile irons of this type with spherical graphite are becoming widely accepted for application at low and high temperature, under certain corrosive conditions and where the castings must be non-magnetic. Since these irons have a much lower carbon content than their low alloyed counterparts, running and feeding, mould rigidity etc. demand even closer attention, if sound castings are to be obtained. The presence of free cerium, from mischmetal additions, can affect graphite form, especially with high purity base irons. However, both these topics are of sufficient complexity to necessitate separate papers, and therefore cannot be covered in any detail in this paper.

SUMMARY OF CURRENT TRENDS

The author offers no apologies for his inability to present anything new or revolutionary in this paper, since it is clear that the production of SG iron is now passing through a period of consolidation, after the dynamic early years that followed its invention.

Producers are more involved at present in serious consideration of economics, more efficient melting, moulding and quality control systems, and it is doubtful whether the basic well-established procedures will be changed dramatically in the near future. However, a few final words concerning current trends may be appropriate:

- There is a strong tendency away from heat treatment to 'as-cast' ductile SG iron, using charges containing a proportion of high purity iron.
- More firms are installing induction furnaces and cupolas of improved design, than at any time before.
- The importance of using rigid moulds is becoming widely accepted and has led to the installation of a large number of rapid cold set resin sand mixers, in association with modest degrees of mechanisation.
- The author believes that large, highly mechanised foundries will install low rated induction furnaces, possibly of the channel type, in which to hold magnesium treated iron at the desired temperature.

Such practice, involving neutrally lined furnaces, which was proved to be feasible by INCO as early as 1960, is now applied by a few SG producers in the USA and elsewhere, but not as yet in Britain. Indeed, one Swedish furnaces manufacturer now offers a specially designed induction furnace involving an inert atmosphere for this purpose. It will be appreciated that if this procedure is applied, magnesium treated iron could be tapped at a precise temperature, in virtually any unit quantity, without special ladles or equipment, ready for pouring into moulds and on a similar footing to grey iron.

This could also mean that the number of basic technical control tests can be reduced and merely involve periodic checks of a large volume of metal for graphite structure, rather than testing of individual ladle treatments.

At the other end of the scale, highly mechanised foundries operating with a small number of casting designs in regular production may decide to carry out magnesium treatment within the mould, on the lines of the 'inmold' process developed by the International Meehanite Metal Company.

This procedure has the advantages of virtually instantaneous magnesium treatment and inoculation, and requires a very small addition of magnesium ferro silicon alloy. Magnesium and inoculation 'fade' will cease to be a problem and primary carbides should not occur.

However, it is essential to be certain that the magnesium containing alloy has actually been charged into every mould cavity and quite sophisticated detection equipment may be necessary for this purpose. Furthermore, each individual casting should be considered as a separate treatment and requires to be tested by ultrasonic or some other means, to ensure that the graphite is spheroidal.

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