SOME IMPORTANT ASPECTS OF TECHNICAL CONTROL,
IN THE PRODUCTION OF HIGH-QUALITY
GREY IRON CASTINGS
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Summary: In order to meet the increasing demands for castings of high quality standards, some important features of control are highlighted in this paper. The importance of clear identification of defects is stressed so that the correct course of action can be taken to overcome them.
Introduction
Iron castings play a vital role in almost all branches of engineering, and purchasers of castings are constantly demanding higher standards of quality. Small defects in iron castings, which a decade ago might have been acceptable or rectified in some way, now often result in rejection. This trend has been most apparent in the automotive and hydraulics industries. Foundrymen throughout the world therefore need to understand and control those important aspects of production which result in substandard and defective castings.

In recent years there have been many developments in the technology of iron casting production, particularly in respect of mould and core making processes and machines. There has also been a continuous growth in the use of both electric melting and holding furnaces. As new production techniques are developed, there are invariably new problems with casting quality which require practical and scientific expertise for their solution.

For many years BcIRA has devoted considerable effort and resources to the improvement of casting quality and has accumulated wide and valuable experience in the diagnosis and prevention of casting defects. However, frequent contact with foundries in many parts of the world continually indicates that not only are there new and common problems to solve, but many of the old problems which have been well documented are still encountered daily. It is, of course, beyond the scope of this paper to deal with the entire range of casting defects.

The DISAMATIC range of machines are capable of producing high-quality moulds and castings at very high output rates, and it is important to control all aspects of production to ensure a low incidence of scrap and to derive maximum benefit from the capability of the machine.

The Rigidity of the Mould and Core Assembly
The rigidity of the mould is unquestionably a most significant factor contributing to the soundness of iron castings. Any form of mould swelling or core collapse, as a result of ferrostatic or solidification expansion forces after the mould has been filled, can promote the formation of internal porosity or external sinking. It is, therefore, vital that moulds should be rammed to their maximum bulk density, to minimize mould dilation and to produce dimensionally accurate and sound castings. The degree of mould dilation and hence casting "oversizing" is related to the degree or volume of unsoundness [1,2]. Fig. 1 illustrates the relation between the degree of oversizing on greensand-moulded brake drum castings and the presence of internal porosity. In the particular design of brake drum studied, oversizing of 1.52 mm on the brake wall could take place before any evidence of internal porosity was observed. All those castings which were more than 1.52 mm oversize exhibited varying degrees of unsoundness. Fig. 2 shows a section through a brake-drum casting which had swollen on the outer face, and which exhibits a considerable volume of internal unsoundness.

The manufacturers of moulding machines are generally well aware of the need to design equipment which will produce rigid moulds, through careful control of sand properties, moulds of high bulk density and castings having high degrees of accuracy and soundness are attainable. The DISAMATIC machine is capable of producing moulds of exceedingly high bulk density, and Yamada [3] has referred to the greater consistency of accuracy in castings produced by this machine, than by conventional greensand techniques. To ensure consistency of mould rigidity the equipment must be carefully and precisely maintained according to the manufacturer's recommendations.

An interesting case of deterioration in mould rigidity on a DISAMATIC 2013 machine, resulting in casting unsoundness, was related to inadequate venting of the moulding chamber. Castings which were normally produced to very high degrees of soundness began to exhibit increasing degrees of internal porosity at critical hot spots (heat centres). Visual observations of the moulds indicated a deterioration in the degree of compaction in certain areas. The reduction in compaction was found to be due to severe wear and
blockage of the vents on the moulding-chamber walls, which had gradually occurred over a considerable period of time. Replacement of the side and top plates restored the correct venting to the moulding-chamber, and well-compact moulds were once again produced. This is a practical aspect of DISMATIC maintenance which requires close attention, to ensure the production of moulds to maximum bulk density, and castings to high degrees of accuracy and soundness. It is difficult to detect a gradual decrease in mould compactness by conventional mould-hardness testing, but it is suggested that the mould permeability meter developed by BCIRA [4] could well be used for this purpose. Fig. 3 illustrates the equipment being used to measure mould permeability. Assuming a constant sand permeability, an increase in mould permeability would be an indication of a deterioration in mould compactness.

It must be appreciated that a reduction in mould compactness renders the mould less tolerant to metallurgical variables, such as pouring-temperature and the degree of nucleation of the iron, both of which have effects on casting soundness [1]. The need, therefore, to produce moulds consistently of maximum bulk density cannot be too highly stressed.

Recent trends in core-making have been to produce, wherever possible, hollow cores as a means of economizing in costly core materials. Hollow cores are, of course, a common feature of the shell process. Such hollow and consequently lighter cores have a lower thermal capacity than solid and heavier cores, and promote slower solidification. Any mould swelling or core collapse which takes place, therefore, under these conditions of slow solidification will tend to promote regions of unsoundness. Foundrymen often overlook the possibility of unsoundness being caused by collapse or dimensional instability of the cores, but this can be a most significant factor in promoting internal unsoundness. A further hazard associated with hollow cores is that of liquid metal entering the hollow inside of the core. This can be via the core prints, or by cracking or collapse of the core in localized areas. Hollow cores produced by the shell or hot-box processes should, therefore, for these reasons, be regarded as possible sources of instability which can result in unsoundness.

Lack of rigidity of such cores can be overcome, if found to be necessary, by greensand or a CO$_2$-sodium-silicate bonded sand filling, or shell cores with reinforced backs may be glued together to form a rigid core as shown in Fig. 4.

The Need to Control Pouring-temperature

The control of pouring-temperature is perhaps the easiest feature of technical control in iron casting production, but it is so often neglected. Pouring-temperature is a highly critical factor, since lack of control can result in many different types of defect [5]. For example, high temperature can result in such problems as metal penetration, mould and core distortion, and porosity defects. On the other hand, low metal temperature can lead to mis-runs, blowhole defects from the mould or cores, and subsurface cavity defects resulting from the reaction of slag with the molten metal during solidification. These are just a few of the problems associated with incorrect pouring-temperature. All castings have an optimum pouring-temperature range, below and above which certain defects will occur. It is essential, therefore, that the optimum pouring-temperature range should be established for each casting being produced, and the necessary controls then applied to ensure the lowest incidence of scrap.
Some of the more frequent problems associated with lack of temperature control are now discussed.

1. Low pouring-temperature

a. Manganese sulphide blowholes. Subsurface blowholes which occur predominantly on the top surfaces of castings are often revealed after the first machining operation and are one of the most common types of defect. Their size can vary from about 2 mm to 10 mm diameter, and they may sometimes be seen to contain small particles of slag. Fig. 5 illustrates a gross form of this defect. Metallurgical examination of this defect generally reveals segregations of manganese sulphide particles and areas of slag associated with the defect, as shown in Fig. 6. This type of defect was investigated by Tonks [6], and its cause is due primarily to low temperature but aggravated by high manganese and/or sulphur contents.

During cooling of the metal in the casting-ladle, manganese-iron oxide/silicate slags are formed, which are carried into the mould cavity during pouring. During solidification of the casting they react with the graphite and produce carbon monoxide gas and small spherical blowholes. At a particular pouring-temperature the incidence of the defect increases with increasing manganese and/or sulphur contents. To minimize the occurrence of this defect and yet provide some flexibility of pouring-temperature, particularly at lower levels, many foundries who use cupola furnaces as prime melting units now adopt some form of continuous desulphurisation [7] using a porous-plug vessel, and reduce the sulphur to between 0.06 and 0.08 per cent. At such levels of sulphur and with an appropriate manganese content of 0.55-0.65 per cent a very noticeable improvement in the cleanliness of the metal is observed, together with great reductions in the incidence of subsurface defects. In most cases the blowholes are revealed during machining, but they can remain unobserved beneath the as-cast skin, to promote severe defects in castings which are subsequently vitreous enamelled [8].

b. Fluid slag inclusions. Small isolated cavities revealed during machining, and which occur just beneath the as-cast skin, can be a severe problem. Their size is generally 1-3 mm, and in marginal situations only one or two may occur, but on a brake-drum or flywheel casting they will be sufficient to warrant rejection. BCRRA investigated this problem in automotive castings produced on a DISAMATIC plant and metallurgical examination of a number of defects clearly showed that they were associated with small quantities of a very fluid slag with no evidence of sulphide segregation. Microprobe analysis of the slag indicated it was an iron oxide silicate. It was therefore a completely different type of defect from the previous one discussed. Fig. 7 illustrates the fluid nature of the slag associated with a defective area.

Investigation clearly showed that pouring-temperature was the main factor; at temperatures above 1430°C there was no evidence of the defect in the wide range of highly machined automotive castings which the foundry produced. The pouring-temperature was subsequently closely controlled between 1430-1480°C. It was interesting that modifications to the gating system failed to overcome the problem. It is considered, therefore, that this type of slag may be produced within the mould cavity, and its formation is favoured at lower temperatures and possibly in mould environments low in reducing gases. Yamada [3] reported a similar observation, although he did not actually describe in his paper the precise nature of the defect. It is interesting that his findings also indicated an optimum pouring-temperature range of 1420-1470°C and it is highly probable that the defect which he investigated was a fluid iron oxide slag.
c. Blowholes from cores. Blowing problems are often encountered as a direct result of inadequate venting of cores and in some cases due to attempting to dispense with vents. Modern coremaking processes where the core is hardened in the core box have often contributed to inadequate venting practices. Depending on the design of the core it may be possible to position vent rods in the core box, which are removed when the core is almost cured. Conversely, it may be impracticable to do so if a highly complicated core is designed, in which case jig-drilling of the hardened core may then become a necessary technique. It must be borne in mind that a core weighing 2 kg has a potential gas evolution of about 30 litres, the major part of which must escape through the vents. Fig. 8 illustrates a section of a cylinder block containing gross blowhole defects in the water-jacket wall and cylinder bores. Investigations carried out under production conditions clearly demonstrated that a relation between pouring-temperature and the incidence of the defect existed, as illustrated in Fig. 9. The defect was eliminated by maintaining pouring temperatures above 1395°C. The severity of the defect increased as the temperature fell below 1390°C.

The temperature at which blowhole defects become apparent is related also to the efficiency of the venting system, and by improving the venting system in the core assembly greater flexibility of pouring-temperature is possible. In the case of a water-jacket core, experience showed that through an increase in the efficiency of the venting system, the temperature at which blowhole defects became apparent could be reduced by 30-40°C.

2. High pouring-temperature
High pouring-temperatures promote the oversizing of castings, particularly when associated with non-rigid moulds, and consequently lead to unsoundness [1]. Since the DISAMATIC machine is capable of producing extremely rigid greensand moulds, the use of high pouring-temperatures should not be a real problem, from this point of view. However, it is a factor which must be considered, particularly when complicated cored castings are being manufactured. The incidence of porosity in the machined cylinder bores, as shown in Fig. 10, was related to pouring-temperature as shown in Fig. 11. At pouring-temperatures above 1425°C the incidence of the defect increased considerably.
and at 1460°C about 50 per cent of the production was defective.

Modern electric-melting plant and the ability to duplex cupola-melted iron into large holding-furnaces provide the facility for good control of metal temperature. It is of the utmost importance, however, that the optimum pouring-temperature ranges should be determined for the types of casting being produced, and then to ensure that they are accurately and consistently controlled.

One of the commonest causes of low pouring temperatures is the rapid loss of temperature due mainly to radiation from uncovered ladles. Frequently, metal of correct temperature is tapped from the furnace, but long transfer times and delays before pouring result in high temperature losses. The fitting of insulated lids to the ladle will result in a significant reduction in temperature loss from the beginning to the end of a casting cycle, and therefore make a major contribution to scrap reduction.

**The Importance of Nucleation**

1. **The effect of inoculation practice**

   The inoculation of grey cast iron with such materials as ferrosilicon, calcium silicide or graphite is a widely used technique to overcome the formation of carbides, or chill in castings and to promote a satisfactory and uniform distribution of graphite.

   Inoculation is, therefore, a useful technique to ensure satisfactory machinability. It is not always appreciated, however, that this treatment increases the risk of unsoundness in grey iron castings. Highly nucleated irons, such as those which have been heavily inoculated, are more prone to contain unsoundness defects than irons having low degrees of nucleation [1], and which have a greater tendency to form carbides. To achieve maximum levels of soundness it is therefore advisable only to use minimal levels of inoculation, which are sufficient to prevent chilled edges, to adjust composition [9]. The prevention of chilled edges is always of concern to foundrymen, particularly for castings which are machined on high-speed automatic lines. It is not, therefore, surprising that in these cases excessive degrees of ladle inoculation often take place.

**Fig. 12** Effect of level of nucleation on soundness of chute pressure plates.

(a) Sound casting, low level of nucleation
(b) Porous casting, high level of nucleation.
Fig. 13 Increasing holding time of liquid metal increases chilling tendency.

Fig. 14 Effect of non-graphitic and graphitic carbon on chill removal. (Non-graphitic top) (Graphitic bottom)

Fig. 12 illustrates the difference in levels of nucleation in sections taken from porous and sound clump pressure-plate castings; the sound casting has a significantly lower level of nucleation than the defective section. The foundry producing these castings was over-cautious and inoculated the iron with both ferrosilicon and graphite to prevent the formation of chill at free edges, particularly in the lugs which are illustrated in Fig. 12. Investigation clearly showed that by reducing the degree of nucleation (by using less inoculant, particularly the graphite) sound castings which were free from chill could be produced. The careful use of a chill test [10] enabled the foundry to minimize the amount of inoculant used, consistent with the avoidance of chill. It is therefore advisable to use only the minimal amount of inoculant, in conjunction with a suitable chill test, necessary to eliminate chill and achieve the desired structure.

It must be appreciated that the thermal conductivity of moulds with very high bulk density, as produced on a DI-SAMATIC machine, is higher than in conventionally produced moulds. The solidification rate of iron will increase with increased thermal conductivity (and bulk density) and there will therefore be a greater tendency for chilling to occur. It is necessary that careful control of nucleation should be achieved to prevent chill formation in critical areas of castings.

In cases where heavy inoculation is required to overcome carbide formation in thin sections, and there is an associated risk of unsoundness occurring, the use of the strontium-bearing ferrosilicon inoculant, developed by BCIRA and reported by Dawson [11] (known as Superseed*) can be very useful. For the same reduction in chill depth as for other commercial inoculants, Superseed produced a lower number of eutectic cells (i.e. a lower degree of nucleation) and therefore less tendency to promote unsoundness [12].

2. Holding and superheat temperature

During the past decade there has been an increasing tendency for iron and steel to be directly produced in electric furnaces, and duplexed through channel holding furnaces. The use of these electric furnaces has enabled the foundryman to use cheaper raw materials, notably steel scrap, to provide higher temperatures, and to hold large volumes of liquid metal for indefinite periods of time. Increasing superheat temperature and holding-time (Fig. 13) both reduce the level of nucleation and therefore increase the tendency for chill formation [13].

In cold furnaces it is important that both of these factors should be carefully controlled. Otherwise sporadic variations in chilling tendency will occur with irons which normally would be of satisfactory composition. Excessively high superheat temperatures and long holding-times must therefore be avoided.

Experience with large electric channel holding furnaces has indicated that, provided they are well-sealed, metal can be held over weekends and even longer periods of time without any significant changes in chilling tendency. Obviously, it is desirable over these long holding periods to minimize the holding temperature in the interests of both power economy and metal characteristics.

3. Carbon additions

Carbon can be used to carburize melts based on steel scrap produced in the electric furnaces, to increase marginally the carbon content of cupola-melted irons, or as a ladle inoculant. The usual materials are petroleum and/or metallurgical coke, or graphite, the form of the carbon being different, the cokes being amorphous and the graphite crystalline. Moore [14] has shown that the graphite-crystalline carbons are potent inoculants, whereas the non-graphite amorphous materials are poor inoculants. Additions of different types of carburizer can therefore promote changes in chilling tendency. For example, a trimming addition of 0.3 per cent carbon to a batch of molten iron by means of petroleum coke which is non-graphitic would have little effect on the degree of nucleation, whereas a similar addition of a highly graphitic material would have a marked inoculating effect: Fig. 14 illustrates this. So changes in the type or source of carburizer can result in the production of irons having differing chilling and porosity tendencies. The use of the para-crystalline graphite will have a strong nucleating effect, whereas the cokes will have little effect on nucleation.

4. The role of sulphur

Since most steels contain very low sulphur contents, the exclusive use of steel scrap in electric-furnace melting will result in irons having low sulphur contents, often below 0.05 per cent. Whilst the value of low sulphur contents has

*Superseed is a registered Trade Mark of Union Carbide Corporation in U.S.A.
been previously referred to, levels below 0.05 per cent in flake graphite irons render them unresponsive to many inoculating additions. Moore [14] also showed that in low-sulphur irons the lack of response to chill removal with graphitic and silicon-based inoculants was due to the exceedingly high fade rates which took place in such low-sulphur irons.

It is not uncommon, therefore, for foundries using high steel-scrap charges in electric furnaces to encounter problems with chilling and poor graphite structures, owing to low sulphur contents even after inoculation. In these circumstances, many foundries find it necessary to add iron sulphide, or to use a proportion of carburizer having a relatively high sulphur content, to arrive at a final sulphur content in the iron of above 0.05 per cent, and then to ensure adequate response from the inoculant.

Some Problems Due to Scrap Contamination
Modern melting technology, involving the use of both electric and cupola furnaces enables the foundryman to use high percentages of steel scrap, to produce high-grade, high-
1. The effect of aluminium

The presence of aluminium in grey cast iron at levels above 0.004 per cent promotes the pick-up of hydrogen by the molten iron [15] from moisture or steam in the mould environment or in damp refractories. On solidification of the iron the hydrogen may be liberated as small pinhole defects just beneath the as-cast surface, or as larger fissure defects in heavier sections. Fig. 15 illustrates a gross form of hydrogen pinholing in an iron containing 0.02 per cent aluminium, which is a high degree of contamination. The defects are fairly characteristic, since they exhibit a shiny surface due to a continuous graphite film which can be clearly observed by careful metallographic examination, and is illustrated in Fig. 16. Such gross contamination is almost invariably due to pieces of aluminium components contaminating the steel scrap, or cast iron scrap if it is used. Fig. 17 shows a number of aluminium-based components present in a supply of steel scrap, and this form of contamination was responsible for the degree of pinholing in the casting shown in Fig. 15.

Hydrogen pinholing in an isolated form is a much more difficult and irritating problem to overcome. It can be quite serious in castings which are extensively machined, and those which are subjected to very high standards of inspection. Such castings are brake discs and drums, clutch pressure-plates and flywheels. Fig. 18 illustrates a brake disc containing isolated cavities due to hydrogen. The aluminium content of the iron was 0.005 per cent, which in this type of casting is sufficient to promote isolated defects which will cause rejection. It is BCIRA's experience that to eliminate this type of defect in the castings referred to, the aluminium content of the iron must be below 0.004 per cent. To achieve this level, extreme care must be exercised over the quality of the steel scrap (or any cast iron scrap) to ensure that it is not contaminated with aluminium.

A further source of aluminium is the ferrosilicon, since this material can contain up to 2.5 per cent of aluminium. If high-strength charges are used, substantial quantities of ferrosilicon will be required, often sufficient to result in iron containing dangerous amounts of aluminium. To achieve low scrap rates and the high quality demanded by the automotive industry in particular, many foundries are finding it increasingly necessary to use ferrosilicon with less than 0.2 per cent aluminium in the furnace charge.

Silicon-bearing inoculants are also a source of aluminium, since inoculating grades of ferrosilicon contain up to 2.5 per cent of this element. With a marginal level of aluminium in the iron as tapped from the furnace, for example 0.003 per cent, a heavy inoculation treatment with ferrosilicon could provide enough further aluminium to create hydrogen pinholing. The selection of low-aluminium inoculating grades of ferrosilicon may under certain circumstances be necessary. Supersil, the inoculant developed by BCIRA, contains less than 0.5 per cent aluminium and is particularly useful when there is a danger of hydrogen pinholing due to marginal levels of aluminium in the iron.
2. The problem of lead

The contamination of flake graphite irons by lead can cause the precipitation of an unsatisfactory or Widmanstätten form of graphite, as shown in Fig. 19. Levels of lead as low as 0.004 per cent have been shown to promote this form of graphite, more so in heavy sections of castings, although the presence of hydrogen is also necessary. Since aluminium causes hydrogen pick-up, lead in irons containing aluminium can be particularly dangerous.

The most significant effect of the Widmanstätten form of graphite is on the tensile properties of the iron; reductions in tensile strength of 50 per cent are frequently observed. A foundry without the facility to monitor lead and having a contamination problem would most probably notice a reduction in tensile strength for no apparent reason, and sporadic outbreaks of cracking. A real hazard exists when castings contaminated with lead are successfully processed in the machine shops, since they may fail prematurely in service owing to fatigue [16].

Contamination of the iron with lead is becoming a more prevalent problem; this is frequently due to the use of free-cutting steel scrap containing lead, or lead-bearing components or even sheet steel coated with lead. This latter material, known as Ternaire plate, is widely used for automobile petrol tanks, and if it is baled with other pressed-steel scrap and used in the ironfoundry it can create serious problems. Very careful control of steel scrap quality is therefore essential to exclude all sources of lead, and it must also be appreciated that during melting the loss of lead is less in electric furnaces than in cupola furnaces.

3. The importance of phosphorus

Phosphorus is always present in grey iron castings and can range between 0.02 per cent to 1.3 per cent. In recent years there has been a very noticeable increase in casting quality requirements, particularly for soundness, strength and machinability, to meet these demands, raw materials having low phosphorus content have been used to a greater extent, and of course the use of high percentages of steel scrap have been most useful.

Phosphorus in cast iron forms low-melting-point eutectics which solidify at some 200°C below the iron-carbon-silicon eutectic, and segregate to the cell boundaries and heat cements. The phosphide eutectics undergo both liquid and solidification contraction, which can lead to unsoundness.

The producers of castings requiring high degrees of hydraulic soundness are generally aware of the importance of maintaining low levels of phosphorus to achieve this, and usually aim for levels of phosphorus below 0.12 per cent. Experience has frequently shown, however, that in complex designs, where very high degrees of soundness are required, phosphorus contents of less than 0.06 per cent are necessary.

Foundrymen are experiencing increasing difficulty in obtaining good-quality steel scrap; it is not uncommon to find steel scrap is contaminated with cast iron components. Some of the cast iron components may contain significant levels of phosphorus, which could lead to undetected sporadic increases in phosphorus content from 0.06 per cent to as much as 0.15 per cent for only one or two ladles of metal. Castings produced from this contaminated iron could exhibit unsoundness in critical areas, and result in an unaccountable increase in machine-shop rejects. Fig. 20 shows a range of cast iron components containing various phosphorus contents which were found in a supply of steel scrap used in the production of high-grade, low-phosphorus pressure-tight castings. The use of this contaminated steel scrap produced sporadic increases in phosphorus content of the resultant iron, and Fig. 21 shows how the rejection rate of cylinder heads at pressure testing followed very closely the variation in phosphorus content.

Whilst it is desirable to use irons having phosphorus contents of less than 0.06 per cent to achieve high degrees of soundness, there is a disadvantage. Levelink & Julien [17] showed that in cylindrical test castings, severe metal penetration occurred when irons having phosphorus contents of 0.03 per cent were used, but the degree of penetration decreased as the phosphorus was raised. Fig. 22 illustrates isolated metal penetration in a small piston, which resulted in considerable setting costs. The problem was overcome by raising the phosphorus content from 0.04 per cent to 0.15 per cent.

Similar observations were reported by Spengler & Ashley [18], who refer to substantial cost savings in setting of grey iron castings by a number of U.S. foundries after raising of the phosphorus content.
The level of phosphorus can therefore be critical, and continual monitoring of this element is a vital part of metal control. It cannot be stressed too strongly that before any action is taken to increase the phosphorus content in an endeavour to overcome a penetration problem, careful consideration must be given to the possible adverse effects on soundness which may result.

Nitrogen — Its Effect on Casting Quality

1. The occurrence and effects of nitrogen in cast iron

Nitrogen may be absorbed by liquid iron during the melting process or filling of the mould cavity, and levels of between 0.004 per cent and 0.009 per cent are common in commercially produced grey iron. At these levels nitrogen can have beneficial effects — promoting fully pearlitic structures and raising the tensile strength. At levels above 0.009 per cent, the iron is less able to retain the gas, which is liberated during solidification to form pinhole or fissure-type defects, sometimes in combination with hydrogen.

In electric-furnace melting it may be necessary to add substantial quantities of carburizer to produce the desired carbon content and the level of nitrogen in the carburizer is important. Some petroleum coals may contain up to 0.5 per cent nitrogen, whereas the high-purity graphite contains as little as 0.0015 per cent. It is important, therefore, to know the nitrogen content of the carburizer in use and to be able to calculate the percentage added by the carburizing treatment. For example, a carburizer containing 0.3 per cent nitrogen can contribute 0.003 per cent of the element for every 1 per cent carbon addition, a 5 per cent addition would certainly result in an iron having a tendency for fissure defects to occur. Davison and others [21] encountered gross nitrogen-fissure defects in large castings after conversion from cupola to electric-furnace melting. The principal source of nitrogen in the electric-furnace charge was from Gilsomite — a carbonaceous material (used as a carburizer) containing up to 2.4 per cent nitrogen, through the use of a Mexican graphite containing only 0.1 per cent nitrogen the problem was overcome.

It is necessary, therefore, to know the nitrogen content of carburizers being used, so that the addition of significant quantities of the element to the melt will be avoided.

Work has indicated that holding liquid metal in an induction furnace may either increase or decrease the nitrogen content until it attains an equilibrium level — depending on the total carbon content, and being higher in low-carbon than in high-carbon irons. This is very important, since the high nitrogen contents produced from high-carbon scrap charges (in either induction or cupola furnaces) can be reduced by holding.

2. The melting process as a source of nitrogen

The cupola furnace is the most widely used means of melting cast iron, and during the past decade there has been a noticeable trend towards using higher proportions of steel in the charge. A number of workers [19,20] have observed a progressive increase in the nitrogen contents of irons as the percentage of steel is increased. Many foundries have noted that irons produced from high-steel scrap charges (say in excess of 50 per cent) are prone to fissure defects. Generally, irons produced with low percentages of steel scrap in the charge, i.e., 15 per cent, will contain between 0.003 and 0.005 per cent nitrogen, and those produced from high-steel scrap charges, i.e., above 50 per cent, between 0.007 and 0.013 per cent nitrogen. Experience has shown that when the nitrogen content of the iron is greater than 0.008 per cent casings are prone to fissure defects of the type shown in Fig. 23. Metallographic examination shows the defects to be interdendritic, as shown in Fig. 24, containing discontinuous graphite films, and the graphite structure may be compacted, as in Fig. 25, and which is typical of high-nitrogen material.

In borderline cases it may often be found that the nitrogen content of the iron may be reduced to a safe level merely by reducing the steel content by 5 per cent and replacing it with either pig iron or suitable cast iron scrap.
4. Nitrogen pick-up from the binder system

Many of the modern resin/catalyst systems contain nitrogen, the level of which can vary widely. Some resins may be nitrogen-free (e.g. phenolics), whereas others having high proportions of urea may contain up to 15 per cent nitrogen. In the hot-box process the resins are capable of curing rapidly when heated in the presence of a suitable catalyst, such as ferric chloride, ammonium salts or dilute phosphoric acid. In the shell process the resins used are phenol formaldehyde, which are nitrogen-free, but hexamine, which contains 40 per cent nitrogen, is used as a catalyst to harden the resin when heated.

During filling of the mould the binder systems decompose, for example ammonia is a decomposition product of urea and hexamine, which will dissociate to free nitrogen and hydrogen. The ammonia salts used to catalyse the hot-box resins are a further source of nitrogen. The nitrogen and possibly some hydrogen is absorbed by the liquid metal and on solidification forms pinhole or fissure defects of the type shown in Fig. 26.

Generally, shell sands are quite low in nitrogen, but if the resin (and hence hexamine) content is higher than normal to give high strength, dangerous levels of nitrogen can result, and pinholing on casting surfaces adjacent to shell cores may occur.

Experience at BCIRA has shown that if the nitrogen content of a resin-bonded sand is more than 0.15 per cent, there is a serious risk of pinhole or fissure-type defects in castings, levels of nitrogen over 0.25 per cent are likely to produce gross forms of the defect.

Resin manufacturers will generally quote the nitrogen content of each type of resin/catalyst system, and it is therefore a simple matter for a foundry to calculate the expected nitrogen content of a sand/binder mixture.

To ensure freedom from such defects, suitably low-nitrogen resin/catalyst systems must be used (in at least quantities compatible with the required properties) to give cores containing less than 0.15 per cent nitrogen. This can be achieved by using minimal amounts of binder, or by deliberately selecting binder systems with low nitrogen content.

Figure 26: Nitrogen fissure defects in hydraulic control valve due to high nitrogen content of core material.

Figure 27: Some hot distortion curves and their influence on casting quality.

Dimensional Problems Associated With Cores

High-speed automated machining systems require dimensionally accurate castings, and the accuracy of sections is desirable from engineering and performance stand-points. The use of high-pressure moulding techniques for mould-making has in general overcome dimensional problems associated with the external faces of castings. The major dimensional discrepancies which are now encountered are related to core instability during mould filling and subsequent solidification of the casting.

There are two principal factors which influence dimensional instability of cores; these are design, and the high-temperature properties of the sand/binder system. It is proposed here to discuss the latter factor only.

During the heating of any core, an initial expansion takes place followed by plastic deformation, and in some instances a secondary expansion may occur. These high-temperature properties depend on the base sand used, and on the breakdown properties of the binder system. A knowledge of these properties can assist the foundry in predicting the suitability of a sand/binder system to meet the dimensional requirements in a specific cored section. The cold properties of a core give little indication of the dimensional stability at elevated temperatures.

An apparatus which rapidly determines the high-temperature characteristics of core specimens has been developed at BCIRA by Morgan [22]. Hot-distortion curves produced by the apparatus clearly indicate the expansion and thermoplasticity characteristics of a core compact. Fig. 27 illustrates such curves for a series of core materials, and their interpretation in relation to the influence on casting quality. Core D1 has high expansion and could give distortion...
problems, whereas Core C has low expansion and would be expected to give satisfactory dimensional stability.

Sporadic outbreaks of core distortion may be the result of a number of factors, such as a change in resin type or formulation, the quantity of binder present, degree of curing or ageing of liquid resins – all of which can modify the high-temperature properties of the core. Three of the commoner variables likely to occur in the core-shop are discussed below.

1. The effect of curing time and temperature
The initial expansion and hot plasticity of shell and hot-box sands is directly related to the curing time and temperature [22]. Excessive curing times give cores with high initial and secondary expansion, a condition which is conducive to distortion problems, conversely, gross undercuring gives low expansion and rapid collapse of the core, as indicated in Fig. 28. It is, therefore, vitally important that strict control should be exercised over the curing cycle and temperature, to produce cores having consistent high-temperature properties. This feature of control will minimize variations in dimensional stability of the core, and contribute to the production of castings having consistent dimensions.

2. The effect of core coating practice
A high proportion of cores are coated with a refractory wash. It has been shown [22] that the depth of penetration of the refractory wash into the surface of a core can have a significant effect on core distortion. Fig. 29 illustrates the effect of two different core coatings on a water-jacket core produced by the hot-box process. The secondary expansion in the untreated core, which can be responsible for core distortion, was only slightly reduced by the application of coating B. Coating A contained 0.1 per cent of a surface activating agent and produced deep penetration which eliminated the secondary expansion. This shows that the type of coating can have a profound effect on the expansion characteristics of a core, and consequent dimensional accuracy of the cored passageways. The preparation and control of refractory coatings and blackings is therefore an important element in core production for accurately dimensional castings.

3. The influence of resin ageing
Resin binders are unstable materials which gradually polymerize, or age, on standing at room temperatures. Most present-day binders have useful lives, i.e., shelf life, of up to three months. Work has shown that some reactive resins which have been stored for periods exceeding three months may produce cores which have high-temperature characteristics different from cores manufactured from fresh resin. Normally, the changes which occur during the manufacturers' recommended storage life have an insignificant effect on core properties, but if this period is exceeded higher-than-normal core expansion on heating may be experienced, resulting in core distortion or cracking. It is generally advisable to use resin binders within three months of manufacture, or the stipulated life given by the resin manufacturer. Storage and use of binders should be on the basis of 'first in, first out'.

The above factors are only some of the variables which can occur during core manufacture. A more comprehensive discussion of core-production variables and their effect on the high-temperature properties has been reported by Morgan [22].

Concluding Remarks
This paper has highlighted some of the important features of control which are considered necessary to achieve and maintain high quality standards in grey iron castings. Some of the problems and their solution are well known, and yet frequently foundrymen fail to exercise the necessary controls. Some of the other problems referred to are the result of modern technology, and the controls necessary to overcome them are not so well known.

In BCIRA's experience the first step is always to identify clearly the defect by metallographic and microprobe exami-
nations. Additionally, analysis of the material by conventional and spectrographic means is essential, the results of which are necessary to augment or reinforce metallographic diagnosis. Once the correct diagnosis has been made the correct course of action to overcome the defect is generally quite clear.

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