Experiences in the Manufacture of Ductile Irons

M. J. Fallon
INTRODUCTION

Ever since the discovery of ductile iron, BCIRA has been heavily involved in advising on its production and providing solutions to a wide range of quality related problems. Even today, 50 years after the original discoveries were made, BCIRA's Membership Services are still giving advice at the rate of about 250 enquiries/year. Most producers are fully aware of the various process routes, and indeed have often been using the same system for many years. The enquiries are therefore usually associated with casting quality problems rather than process operations and their frequency and repetition allows them to be categorised. Quite clearly there are three principal areas of difficulty and these are as follows:

A. Problems associated with the casting surface.
B. Difficulty in achieving the desired mechanical properties and performance.
C. Problems with running systems and the avoidance of shrinkage porosity defects.

Some of the most common problems related to these areas of difficulty are described below.

A. Problems associated with the casting surface

1. Graphite nodule flotation

Graphite nodule flotation is a problem which is regularly investigated by the Membership Services department at BCIRA.

The defect is often evident on ductile iron castings as a surface fault comprising a poor surface finish and blowholes in combination with dross, because as the graphite nodules float, they have a scavenging effect on entrained particles. Typically the defect appears on as-cast top surfaces and on the underside of cores. If the casting is sectioned, the higher number of nodules close to the top surface is clearly evident, as illustrated in FIG 1. Metallographic examination usually shows the greater concentration of nodules to include some exploded hyper-eutectic nodules. The visual appearance of the casting top surface can vary considerably and in some cases graphite flotation may not be evident until the casting is machined. Under these circumstances flotation is normally revealed by the presence of dark patches on the top surface, or a darker layer at the top of sidewalls and the underside of cores.

Graphite flotation is caused by pouring iron of hyper-eutectic composition and is aggravated by the presence of heavy sections, where the solidification rate is slower. Most ductile irons are poured close to, or at the eutectic composition of about 3.6% C and 2.6% Si and at these values are exceeded, flotation becomes increasingly more likely. The presence of graphite flotation reduces tensile properties. In critical areas it can have a devastating effect on fatigue properties and very small amounts have been shown, for example, to produce fatigue failure when present at the machined surface of horizontally cast crankshaft journals.

2. Dross stringers

Dross stringer defects comprise magnesium oxide/sulphide/silicate compounds. It is possible to see them in all areas of a casting, but normally they are often found at top surfaces and at the underside of cores, due to flotation. A typical example is shown in FIG 2 and because of the local presence of sulphur in the dross, there is often flake and compacted graphite surrounding the stringer defect. The extent of the defect can vary from isolated small stringers to severe cases of surface lapping, which is often associated with reaction blowholes.

The formation of dross stringers is created and aggravated by the use of turbulent running systems and pouring practice, especially when cold metal is poured, because oxidation takes place more rapidly at low metal temperatures. Another reason is the treatment of high sulphur irons and/or the use of high residual magnesium contents. Initial sulphur contents should be below 0.02% (preferably below 0.01%) whereas residual magnesium contents should not exceed 0.05%. Foundries that operate with very low sulphur levels of about 0.005% and can therefore successfully produce at residual magnesium contents of 0.04%, generally have less of a problem with dross related defects. Dross stringers are aggravated also by using compositions which are hyper-eutectic.

Industrial experience has shown that ductile irons treated with pure magnesium using plunging, reaction vessels or magnesium containing wire tend to have less problems with dross defects. This is considered to be because magnesium ferrosilicon contains trace amounts of aluminium and calcium of up to about 1%, which also react and oxidise during the treatment process.

The presence of dross stringers in the centre of heavy sections is unlikely to have an adverse effect on properties. At cast and machined surfaces, however, they act as stress raisers and are likely to promote failure in fatigue conditions.

The development of metal filtration technology over the years has considerably reduced the incidence of dross problems; however, they have not been entirely eliminated. Reasons are given in the section related to metal filtration.

Dross stringers are often mistaken for cracks by customers using magnetic or red dye-penetrant testing. Under these circumstances the castings are usually rejected as containing 'crack-like indications'. Arguments that the castings are not cracked are usually futile because dross stringers can and do act as cracks under service-stressed conditions.
3. Structures under denseners

Denseners used to eliminate shrinkage defects do so by locally increasing the solidification rate. In the process they can also modify both the graphite and matrix structure, resulting in the presence of faint ghostlike marks on the machined surface. These have often been observed on densened castings and have occasionally resulted in rejection. The high local solidification rate causes the formation of a large number of small graphite nodules and these are invariably associated with ferrite. Because of the slightly different colour of ferrite compared to perlite and the different machining characteristics, the visual appearance is locally altered. In extreme cases fully perlite ductile irons have local surface patches comprising a very high nodule number in a fully ferritic matrix.

An example of this structure is shown in FIG 3. It is normally excessively large denseners in either cast iron or graphite which cause this type of phenomenon. Remedial action involves either reducing the thickness of the densener in use, or alternatively changing to a less thermally conductive material, such as silicon carbide.

4. Flake graphite rims

Flake graphite rims can occur on the surfaces of ductile iron castings and if they are not removed during subsequent machining operations, will cause localised reduction in mechanical properties. This can have serious consequences in castings subjected to fatigue stresses during operation.

An example is shown in FIG 4. Flake graphite rims are always associated with sulphur pick-up from the moulding or core sand. There may also be oxidation of magnesium which lowers the residual magnesium content, especially in greensands with a low volatile content, which promotes oxidising conditions. The extent of the rim depends on the type of sand employed and its sulphur content. Examples have been seen of a complete rim where moulding and core sand are the same, and also rims which are confined to either the mould or core surfaces when different sands are employed.

If flake graphite rims are to be avoided, it is necessary to ensure that the moulding sand sulphur content is below 0.15%. This should only be regarded as a guide, however, because in highly susceptible areas such as metal surrounding a thin cod of sand, the limiting value may be lower. In greensand moulds the sulphur is picked up from the coalsand and any build-up of sulphur rich fines.

Greensand systems should remain under satisfactory control if the content of residues from spent coalsand and clay is limited by the regular addition of new sand, a typical renewal rate being 1.5–2.0% of the sand in circulation. If sulphur control is found to be difficult in these circumstances, for ductile iron production low sulphur coalsands containing less than 1.0% sulphur are available, together with sulphur-free coalsand substitutes or blends.

Sulphur is only picked up from chemically bonded sands if the binder has been catalysed with one of the sulphonic acids. Common causes of high sulphur levels in chemically bonded systems are poorly maintained and calibrated mixers and the use of excessive volumes of weak acid in cold weather in an attempt to maintain an acceptable curing rate. Equipment should be well controlled and acid levels should ideally not exceed 50% of the resin.

In reclaimed sand systems the build-up of sulphur rich residues results from ineffective size classification, which is usually traced to poor maintenance. The use of 100% reclaimed sand should be avoided and typically, additions of between 5% and 25% of new sand are made. Failure to add sufficient new sand has been known to result in reclaimed sands with sulphur contents of 0.3–0.5%.

Experience has shown that the application of mould coats are generally ineffective in eliminating sulphur pick-up from the mould.

5. Phosphorus pick-up

Phosphorus pick-up occurs due to mould/metal reaction, resulting from the use of phosphorous acid catalysts in chemically bonded moulding systems. Phosphoric acid is usually used to replace sulphonic acid in situations where the amount of sulphur dioxide and hydrogen sulphide fume generated after curing has been found to be unacceptable.

Examination of ductile iron castings produced in new-sand moulds has shown localised surface pick-up of phosphorus, as shown in FIG 5. The exact mechanism is not completely understood, but may be related to the formation of elemental phosphorus by reaction between phosphates, carbon and silica in the mould. Investigations have shown that the presence of localised high concentrations of phosphorus at the surface produces a slight reduction of about 3–5% in the mechanical properties of ductile irons. This may, however, be greater in heavy sections, where the pick-up would be expected to be greater.

Far more significant effects have been observed in castings produced in reclaimed sand mould catalysed with phosphoric acid. Under these circumstances a build-up of phosphates occurs in the sand system, even in units with highly efficient reclaimers and these can produce outbreaks of severe surface pitting defects. Industrial experience has shown that the likelihood of pitting defects and their severity are dependent on the phosphate (PO₄) content of the sand and the section thickness being poured.

Heavy sections are particularly susceptible, especially when poured into moulds having high phosphate contents, i.e. PO₄ levels in excess of about 0.75%.

Foundries experiencing pitting defects when using phosphoric acid catalysts usually find that the phosphate level in the sand is about 1%. The only satisfactory method reducing the phosphate content of the sand is to increase the new sand addition and a typical sand mix for use with phosphoric acid would contain about 60% reclaimed sand and 40% new sand. Mould coats based on magnesite have been shown to minimise the problem, but can be ineffective in re-entrant sections which act as a hot spot.

6. Dross pitting

Dross pitting defects are regularly observed at BCIRA, characterised by the presence of a rough and pitted cast surface where the pits are filled with a white powder or fibrous deposit. The deposit is quite soft, can easily be
removed and in cases where heavy shotcleaning is employed, the initial evidence may be destroyed. It has been observed in castings made in silica, chromite and zircon sands and is prevalent at top surfaces, at hot spots, at gates and adjacent to feeder necks.

FIG 6 shows the typical appearance of the defect in a hot spot caused by a re-entrant corner of a heavy section ductile iron. Metallographic examination shows the pits to be lined with a mixture of silica or iron silicate in a matrix of iron oxide. The defect occurs when the mould conditions are insufficiently reducing, because of a low volatile content in the moulding sand. It is also aggravated by a high silicon content in the iron and by high pouring temperatures. In one instance, where heavy ductile iron castings were specified to contain 3.0-3.3% Si, the defect was eliminated by an addition of coal dust to the furane moulding sand in order to raise its volatile content. Similar types of defects have been seen on castings made in greensand and this was because of a build-up of spent coal dust and dead clay, together with a low volatile content.

7. Surface oxide scale following heat treatment

The presence of retained surface oxide scale following shotcleaning also has an adverse effect on machinability by increasing tool wear. Differences in tool life when machining castings from two different foundries, especially in cases where high speed repetitive machining is involved, has been related to quite small differences in casting cleanliness. Such problems have been overcome by improved heat treatment and shotcleaning practice.

B. Difficulty in achieving the desired mechanical properties and performance

1. The Basic Properties

The mechanical properties of ductile irons containing well formed nodules are essentially dictated by the matrix structure. This is the opposite of grey irons, where strength is mainly controlled by the graphite size and form.

The speed of solidification of thin section ductile iron castings normally promotes an acceptable graphite form and failure to meet the required properties and performance are usually related to the presence of too much, or too little pearlite, and/or the presence of eutectic carbide.

As section size increases in ductile irons, properties are lowered. In ferritic irons the tensile strength is largely unaffected although the elongation is markedly reduced, whereas in pearlitic irons the naturally low elongation is maintained, whereas the tensile strength is reduced. These effects are the result of slow cooling causing segregation of trace elements to promote intercellular carbides, the formation of poorly shaped nodules allow nodule number and pearlite with a wide lamellar spacing. Such problems are the usual reason for failure to meet the mechanical properties specified in cast-on test bars, or bars cut from the heavier sections of sample castings, as opposed to separately cast keel blocks.

2. Properties in Thin Sections i.e. up to about 50 mm

In thin section castings the mechanical properties are normally obtained from separately cast keel blocks and the castings are sentenced on the results obtained. Provided that acceptable controls are placed on charge purity, metal composition, treatment and inoculation there is usually little difficulty in achieving the required mechanical properties. Problems with thin castings usually occur in the machine shop and are related to the presence of carbide and/or unsatisfactory amounts of pearlite and ferrite.

Carbide

BCIRA regularly is involved in machining problems related to the presence of eutectic carbide in thin section ductile iron castings. Often the carbides are present together with very well formed nodules, indicating no apparent difficulty with treatment. Usually the problem is related to poor control of silicon producing a low final level, or more often, poor inoculation practice particularly involving situations where the magnesium treatment alloy and inoculating ferro-silicon are added at the same time.

Occasionally, and particularly in very thin section castings in multi-impression boxes, carbides persist at free edges despite very good inoculation practice. The most satisfactory solution to this problem, assuming that inoculation cannot be improved by, for example, in-mould inoculation, is to make an addition of about 0.02% bismuth (Bi) to give a 10% recovery and thus a 0.002% residual level. This element has the effect of substantially increasing nodule number, the larger number of smaller nodules promoting more ferrite and eliminating carbide. Bismuth additions must be used in conjunction with a cerium bearing treatment alloy.

Pearlite/Ferrite Content

In thin section castings the metallographic structure of the casting often bears little relation to that in the test bar, because of the effects of cooling rate, trace elements, inoculation etc. Particularly in the case of castings containing thick and thin sections, there can be different structures in different parts of the casting. In cases where pearlite promoting elements are present, the natural assumption is that more pearlite will be present in the thinner, faster cooling sections. This is usually not the case. More often the faster cooling thin sections contain a larger number of smaller nodules and this promotes more ferrite. BCIRA has been involved in a number of discussions with designers and engineers who have difficulty in understanding the concept of varying matrix structures in the casting and their effects on machinability. The needs and needs used for pearlitic irons often cause smearing of the
ferrite in the more ferritic areas and conversely, those used for ferritic irons cause higher tool wear when cutting pearlite. A number of complaints of different machined finish in various areas of the same casting have been found to be the result of this situation.

3. Properties in Heavy Sections i.e. above about 50 mm

The mechanical properties of ductile irons are principally dictated by the matrix structure, as opposed to grey irons, where they are dictated mainly by graphite shape and size. Despite this fundamental difference, properties reduce as ductile iron section size increases, although the effects are not the same in pearlitic and ferritic irons. In pearlitic irons, tensile strength decreases in increasing section sizes although the already low elongation is little affected. Conversely, in ferritic irons, the tensile strength is largely maintained as section size increases and elongation is markedly reduced.

These effects are primarily related to an increase in the size of the graphite nodules, deterioration in their shape, a decrease in nodule number and element segregation effects resulting in the formation of intercellular carbides.

Segregation Effects

The adverse effects of segregation associated with slowly cooled large section castings can be reduced by controlling the purity of the charge materials and by increasing the nodule number. An increase in nodule number and improvements in nodule shape in large section castings can be effected by the addition of a small amount of antimony, up to about 0.005%, with a consequential increase in elongation; however, such a practice should be confined to irons where some pearlite in the structure is acceptable. Mainly ferritic irons can be produced containing 0.005% antimony but there can be major problems if this level is exceeded, particularly if other pearlite promoting elements are present such as copper and tin. Bismuth has already been mentioned as an element which increases nodule number; however, it is usually believed that its effects are reduced as the section size increases. Bismuth can be effective, however, particularly when used in combination with late inoculation techniques such as FeSi blocks in the pouring bush. This is shown in the following table comparing bismuth containing irons with a bismuth-free iron having a nodule number of 10/mm² in a 300 mm section.

Additions of alloys which reduce nodule size and increase nodule number can be beneficial in raising mechanical properties of heavy sections or test bars attached to them. This is illustrated in the example given below, from 200 mm sections having a predominantly ferritic as-cast structure.

Chunk Graphite formation

Attempts to obtain high mechanical properties in very heavy sections have not only included the addition of elements such as antimony or bismuth, but have also involved the use of highly pure charges to avoid the formation of intercellular carbides. The use of highly pure charges can result in the formation of chunk graphite as shown in FIG 7, with consequential reductions in the mechanical properties. In heavy section castings production, therefore, particularly when cast-on test bars are involved, there has to be a compromise between using a charge which is sufficiently pure to avoid severe segregation effects and the use of a charge which is too pure and which results in chunk graphite. The chunk graphite form can usually be avoided by deliberate 'contamination', normally using bismuth in the presence of cerium, together with the use of pig iron and carefully selected steel scrap to limit the levels of carbide forming elements in the composition.

<table>
<thead>
<tr>
<th>Bar diameter mm²</th>
<th>Nodule count/mm²</th>
</tr>
</thead>
<tbody>
<tr>
<td>75</td>
<td>240</td>
</tr>
<tr>
<td>150</td>
<td>110</td>
</tr>
<tr>
<td>250</td>
<td>70</td>
</tr>
<tr>
<td>300</td>
<td>60</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Antimony %</th>
<th>0.2% Proof Stress N/mm²</th>
<th>Tensile Strength strength N/mm²</th>
<th>E%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nil</td>
<td>239</td>
<td>414</td>
<td>11</td>
</tr>
<tr>
<td>0.005</td>
<td>299</td>
<td>458</td>
<td>20</td>
</tr>
</tbody>
</table>

4. Avoiding embrittlement and the maintenance of satisfactory impact properties

Pearlitic Irons

Fully pearlitic ductile irons have low impact properties at room temperature and below, usually in the order of about 2-4 joules, Charpy 'V'. It is often not appreciated that these results are very similar to those obtained from a 250 N/mm² grey iron tested under similar conditions.

Although pearlitic ductile irons are rarely specified in situations where impact resistance is important, they are frequently employed where high tensile strength is required.

Standards for ductile iron demand strengths of up to about 900 N/mm² with 2% elongation and the high strength materials, i.e. 700/2 and above, are often alloyed with copper, tin, manganese and some times antimony to produce a fully pearlitic matrix.

On the presumption that more alloy additions mean higher strengths, a number of foundries have added pearlite promoting elements, particularly tin, at greater amounts than are required to produce a fully pearlitic matrix. This does not significantly improve tensile strength and has a powerful embrittling effect, which has caused cracking failures in service under both tensile and low-stress impact conditions. Copper is more tolerant than most of the other
pearlite promoting elements; however, when it is used in combination with others, their levels should be limited to a level just sufficient to promote 100% pearlite. Where higher strengths are required than can be obtained by 'safe' alloying, heat treatment should be considered, which refines the pearlite to give a finer lamellar spacing. Typical examples of high strength ductile iron production routes are given below.

Quenched and tempered irons should have a maximum silicon content of 2% to avoid the formation of seedling nodules, which lower properties.

**Ferritic Irons**

Ferritic ductile iron are employed in impact loading conditions and impact property specifications are present in most standards for irons to be used at room temperature and below.

Lack of control over the metal composition is the normal reason why ferritic ductile iron become embrittled, particularly with respect to silicon content. The large amounts of silicon added during treatment and inoculation and the need to use up return scrap often create a situation where silicon levels rise to above 2.8%. At silicon contents over about 3%, it is possible for fully ferritic ductile iron to crack at very low stress levels, to the extent that they may break even when dropped. This type of silicon embrittlement cannot be removed by heat treatment.

Cracked ductile iron castings which show no evidence of serious abuse and which have fully ferritic matrices can be assumed to have a high silicon content, although analysis will confirm this. Embrittlement is also caused by high levels of phosphorus and by the presence of pearlite, although both of these are evident in the as-cast microstructure. Pearlite can be remedied by heat treatment although phosphide/carbide complexes cannot, an example being shown in FIG 8.

The specifications designed to ensure adequate impact properties at sub-zero temperatures also require specific tensile properties to be met and the combination of tensile and impact properties can be difficult to achieve, especially for impact tests at -40°C.

Typical specified properties for such materials are shown in Table 1, which refers to BS 2789:1985 and DIN 1693:1973. Difficulties in meeting the combined properties for these materials stem from the fact that a low silicon content is required to meet impact requirements and a low silicon content adversely affects tensile properties, particularly proof stress. This latter property has to be met in DIN 1693, but not in BS 2789.

<table>
<thead>
<tr>
<th>Grade</th>
<th>Tensile strength</th>
<th>0.2% proof strength</th>
<th>Impact value, J</th>
<th>Specified Mean</th>
<th>Individual test</th>
</tr>
</thead>
<tbody>
<tr>
<td>400/18L20</td>
<td>400</td>
<td>250</td>
<td>18</td>
<td>12 $ (V)</td>
<td>9 $ (V)</td>
</tr>
<tr>
<td>350/22L40</td>
<td>350</td>
<td>220</td>
<td>22</td>
<td>12 ! (V)</td>
<td>9 ! (V)</td>
</tr>
<tr>
<td>GGG 35.3</td>
<td>350</td>
<td>220</td>
<td>22</td>
<td>14 ! (U)</td>
<td>11 ! (U)</td>
</tr>
<tr>
<td>GGG 40.3</td>
<td>400</td>
<td>250</td>
<td>18</td>
<td>14 $ (U)</td>
<td>11 $ (U)</td>
</tr>
</tbody>
</table>

DIN 1693 also has room-temperature minimum impact values as follows:

<table>
<thead>
<tr>
<th>Grade</th>
<th>Tensile strength</th>
<th>0.2% proof strength</th>
<th>Impact value, J</th>
<th>Specified Mean</th>
<th>Individual test</th>
</tr>
</thead>
<tbody>
<tr>
<td>GGG 35.3</td>
<td>19</td>
<td>17</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GGG 40.3</td>
<td>16</td>
<td>14</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Optional verification + Mandatory verification
$ Tested at -20°C ! Tested at -40°C

Table 1. Minimum requirements for ductile irons with specified low-temperature properties to BS 2789:1985 and DIN 1693:1973.

5. Producing Irons with Specified Low-Temperature Properties

**Silicon content**

To comply with the specified requirements of the low-temperature grades of ductile iron, it is necessary to produce irons having a low silicon content, within the range 1.9-2.1% silicon. This is especially important for irons tested at -40°C, though a slightly higher silicon content up to about 2.25% can be tolerated in irons tested at -20°C.

**Nickel or Copper content**

It is unlikely that tensile and 0.2% proof strength requirements of the German specification will be met without a nickel or copper addition. For safety it is also advisable to consider it for the production of irons in the British Standard. These elements raise the proof and tensile strengths of ferritic ductile iron without having an adverse effect on impact properties. An addition of 0.75% nickel or 0.35% copper should be made, either of which will raise the tensile and proof strengths by about 35 N/mm².

**Trace element levels**

Trace element levels should be as low as possible by the use of high purity charge materials. This applies specifically to phosphorus (<0.02%) chromium (<0.05%) and manganese (<0.2%).

291
Nodule number

The production of an iron having a very high nodule number should be avoided or the minimum impact values at the stipulated temperature may not be met.

Heat treatment

To ensure that the required properties are met, it is usually necessary to heat treat the castings and test bars as follows:
1. Heat to 900°C and hold at that temperature for 1 hour plus 1 hour for each 25 mm of casting section.
2. Furnace cool to 700°C and hold for a minimum of 4 hours. (With high-purity irons and a well controlled heat treatment operation it is possible to obtain fully ferritic structures by cooling slowly from 900°C through the critical temperature without holding. A rate of cooling of 25°C or less per hour is then recommended.)
3. Furnace cool to room temperature.

A sub-critical heat treatment should not be used for the reasons previously described.

Properties in Castings

Generally, properties in castings are lower than in test bars, this applying specifically to heavy sections because the slow cooling rates involved cause deterioration in the nodule form and increase the segregation of minor trace elements to the cell boundaries. The effect of segregation tends to be more important in this respect and in very pure charges, there can be little difference in the impact values between steel blocks and heavy section bars or castings. For example, in a pure base-charge material in the fully annealed condition, the maximum impact value was lowered from 21J in a 44 mm Iec to 18J in a 300 mm section. There was no difference in the temperature at which transition to brittle failure began, i.e. both were 20°C, although the sub-zero properties were somewhat different. At -20°C the impact value was 15J and 300 mm section was 11J. At -40°C the values were 10J and 6J respectively.

In order to meet the requirements of nuclear waste storage, some very heavy section castings are produced in irons requiring high impact values at low temperature. Values obtained in 630 mm sections from high purity charges are between 16J and 19J at room temperature and 8J and 12J at -20°C; these tests being conducted using 'U' notched bars.

The Comparison between Irons and Steels

Although irons can have tensile properties similar to those obtainable from steels and can be an alternative material to steel under conditions of tensile loading, there is no comparison under impact conditions. Generally, the steels have higher specified impact values, and substantially higher impact properties at room temperature. This applies particularly to plain carbon and alloyed steels that have been specifically developed for their toughness and impact resistance. It should be borne in mind, however, that in some cases ductile irons can still be in the ductile range at sub-zero temperatures, while steels are in the brittle range, resulting in ductile irons having higher impact properties under these conditions.

Alloying ductile irons has very little effect on the maximum impact value obtained and generally raises the transition temperature, such that additions are of little or no value. By comparison, alloyed steels can have substantially higher impact properties, particularly the nickel-containing material. Fig. 9 shows these properties and compares two steels developed for toughness applications, compared with three ductile irons developed for the same reason.

6. Problems with Plate Fractures

Plate fractures are commonly seen in ductile iron castings, usually at the feeder neck/casting junction when the feeder is broken off. Its general appearance is shown in Fig. 10. Sometimes it has been observed at the fracture of test bars cut from castings, although it has never been observed in bars taken from keel blocks.

The plate type of fracture is always associated with nodule alignment and the presence of inclusions, as shown in Fig. 11. This results in reduction of mechanical properties, the major effect being on the ductility as shown below:

When such plate fractures are observed, questions are invariably asked regarding the effect on the overall integrity of the castings and their likely service performance. Experience at BCIRA has shown that where nodule alignment occurs, which could possibly extend into a plate fracture, the alignment is usually close to the hot spot created by the feeder neck and diminishes with distance from it. BCIRA has never seen a service failure which can be attributed to nodule alignment/plate fracture.

Research has confirmed that nodule alignment and the simultaneous segregation of inclusions occurs at an early stage during solidification and that the problem is difficult to eliminate. Because most feeders on ferritic ductile irons are cut off, as opposed to broken, it is probable that the incidence of alignment is greater than is apparent. More rigid moulds, higher carbon equivalents, changes to pouring temperature, modified running systems and the maintenance of low magnesium and sulphur levels have the effect of reducing the risk of nodule alignment; however, there is no easy practical solution to this problem.

<table>
<thead>
<tr>
<th>Plate fracture form</th>
<th>UTS N/mm²</th>
<th>0.2% Proof Stress</th>
<th>E%</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td>421</td>
<td>289</td>
<td>21</td>
</tr>
<tr>
<td>Slight</td>
<td>441</td>
<td>310</td>
<td>16</td>
</tr>
<tr>
<td>Extreme</td>
<td>398</td>
<td>283</td>
<td>8.5</td>
</tr>
</tbody>
</table>
7. The effects of microporosity and surface imperfections on mechanical properties

When casting defects are revealed during machining, BCIRA has often been involved in discussions between the customer and supplier regarding the likely effect on properties and performance. These discussions are usually concerned with the influence on tensile and fatigue properties.

Tensile Properties

Work carried out at BCIRA has shown that isolated pockets of centre-line porosity do not significantly reduce proof stress values but that there is a reduction in ultimate tensile strength and elongation. The ultimate properties still, however, remain at a high level - sufficient to guard against an accidental overstress.

As design stresses are based on proof stress values it may therefore be possible to tolerate the reduction in ultimate properties. Only when gross porosity is present are both proof stress values and ultimate properties reduced.

In castings, bending stresses are often more frequently applied than direct tensile stress. Centre-line porosity may then occur in a relatively unstrained area at the neutral axis. Under these conditions microporosity would not be a potential source for the initiation of fracture. Under direct tensile stress this is not the case, because all elements of the structure including unsoundness and non-nodular graphite are maintained at the maximum stress level and failure would occur at the weakest point in the structure.

Fatigue Properties

In the case of fatigue, it has been confirmed that under rotating bending conditions as-cast surfaces approach or equal the fatigue properties of machined surfaces provided that they do not contain surface imperfections. Where microporosity is present in the centre of the section, fatigue properties are not significantly affected. Other work has confirmed that:

a) When porosity is more extensive and is present at or near the surface, the unnotched fatigue properties are reduced to a level dependent on the extent of the porosity.

b) Small amounts of microporosity at or near the surface have little or no effect on notched fatigue properties because the notch has a greater effect than the defect.

c) Flake graphite skins reduce fatigue limit by about 15%.

d) Depending on severity, stringers reduce fatigue limit between about 19% and 33%.

e) Pinholes have the greatest effect on fatigue limit, causing a reduction of about 40%. This produces an equivalent fatigue limit to that obtained in a bar containing a 45° V-notch of 0.25 mm root radius.

C. Problems with Running Systems and the avoidance of Shrinkage Porosity defects

Ductile iron is a cross forming alloy and the purpose of the running system is not only to transport molten metal to the mould cavity, but to do so in a manner which avoids turbulence and oxidation. Traditionally they have always been pressurised and one of the many techniques was developed by Karson. In this particular instance the system sizes are determined by the poured weight, using graphs to establish the choke dimensions, pouring temperature, gate thicknesses, sprue diameter etc. Where moulds are vertically poured as in the case of Disamatic moulding machines, the Kazimierz Hess Nomograph provides a similar method of determining the appropriate sizes.

Pouring practice and pouring bushes are responsible for many diesel and most sand inclusions problems. The pouring bush should be large enough to enable the pourer to position the ladle lip and to keep the bush full at all times, thus avoiding the ingress of slag and breeze. Good and badly designed bushes are illustrated in FIG 12. One of the most important points with respect to pouring is the height of the ladle lip above the bush when the metal is poured. The lip should be as close as is practical to avoid the Bush to prevent turbulence and particular care should be taken to avoid pouring directly down the sprue, because this pressurises the running system to create sand erosion and diesel defects.

1. Pouring

Widespread use is made of slag coagulants to remove slag and breeze from the top of ladles. Such materials should be used with great care because they are alumino-silicates containing bismuth and potassium oxide, which form a liquid glass at about 1100°C. The minimum amount possible should be used to assist pour removal and the mixture of slag coagulant and slag/breeze should be completely removed prior to pouring. Under no circumstances should a layer of slag coagulant be left on the top of the ladle during pouring, because a highly fluid slag will be generated underneath it and will be washed into the mould cavity.

2. Running Systems

Running systems should always be moulded, never cut into the mould cavity. The use of polystyrene runners in large moulds is a convenient compromise between these two extremes, but are consistently successful only if the material has a small head size and the sand is well compacted around it. Removal prior to mould closure and the use of mould coatings on the running system surfaces usually prevents erosion and should be considered essential.

A common fault with running systems is the placement of the ingates beneath the runner bar as opposed to on its side. This creates considerable turbulence because the metal flow along the runner bar is interrupted and dirty metal can
enter the system during the initial stages of the pour. Metal always flows to the end of a running system before filling the ingates, because of the dynamics of fluid flow. For this reason there should always be an extension of the runner bar at least 50 mm beyond the last ingate to trap dross and non-metals being pushed along by the first metal in the system. If the last ingate is close to the end of the runner bar, the non-metals being washed along by the first metal flowing in the runner bar, will be forced into the mould cavity.

3. Filtration

Metal filtration has been used with considerable success to improve the quality of castings by removing non-metals. BCIRA is commonly asked why a casting can contain dross when the system contains a filter. The usual answers are:

a) Rarely - that the filter has broken during the pour, and this only occurs with large filters and high pressures.

3) Sometimes - that the filter has not been installed correctly in the mould.

c) Commonly - that the running system beyond the filter is turbulent or the ingates are in an inappropriate position, for example at the joint line of a job where the majority of the casting is in a deep drag half. This requires re-examination of the system design and revision to a less turbulent fill.

4. Feeding Systems

The basic causes of shrinkage and appropriate feeder systems have been described in detail. The difficulties of feeding ductile iron are considerably greater in greensand moulds than in chemically bonded moulds because of the influence of mould dilution during filling and solidification expansion. Roeder’s method of pressure control risering has considerably eased the difficulties in greensand moulds and BCIRA’s involvement in shrinkage problems is more frequent with respect to the larger castings made in chemically bonded moulds.

It is BCIRA’s experience that many foundrymen do not understand that ‘dispersed’ shrinkage, or microporosity in hot-spot areas, occurs after solidification expansion has occurred and is secondary shrinkage which cannot be eliminated by extra feed. On many occasions castings have been examined where larger and larger feeders have been employed in an attempt to overcome shrinkage difficulties of this type, which are not in any way related to the provision of feed metal. The effect of using larger feeders is simply to aggravate the situation by increasing ferrostatic pressure on the mould and increasing the hot spot effect at the neck. This is the reason why the problem usually persists at, or just beneath the feeder. BCIRA has ‘solved’ more under-riser shrinkage problems by removing risers entirely, than by modifications to riser shape and size.

The typical appearance of shrinkage defects and the associated feeder cavities gives a good guideline as to the cause of the problems. One control measure that foundries rarely undertake at the trial stage or during problem solving is the sectioning of feeders to establish their efficiency or otherwise. If a feeder is completely sound it is probably unnecessary. Normally, however, sectioning of the casting and feeder, or examination of defective castings, will reveal one of the situations shown in Fig 13. Although there are a large number of variables that can affect feeding efficiency, the following are broad guidelines which suggest likely causes of shrinkage.

**Situation A** - This is the ideal situation, where the casting is completely sound due to progressive solidification towards the riser. Solidification of the casting has been assisted by graphitic expansion and the last metal to solidify, which freezes with contraction, is in the feeder. The feeder therefore contains evidence of both liquid and secondary shrinkage.

**Situation B** - Liquid shrinkage cavities are present in the feeder, often almost down to the feeder neck and the thermal centre of the casting contains a large area of secondary shrinkage. This is often indicative of mould movement, which increases the size of the mould cavity and produces an extra demand for feed metal. It is especially prevalent in greensand moulds and also occurs in under-cured chemically bonded moulds and boxless moulds which are insufficiently weighted. Casting swell is associated with this problem, but is not always visually obvious. Careful visual examination should be carried out, possibly together with weighing and measurement of the castings. Although the castings contain a cavity, they are usually heavier than normal, because of the swell that has occurred.

**Situation C** - The casting contains a pipe defect which extends into the casting from the feeder and is clearly visible when the feeder is removed. This is the result of liquid shrinkage into the casting at an early stage of solidification and is normally caused by either a feeder which is too small or a pouring temperature which is too high. A supplementary possibility is that the feeder neck is too large, which in combination with one of the other factors aggravates the hot spot in the neck area.

**Situation D** - When the feeder is removed, the casting is apparently sound, but on machining, a hole defect is revealed often in combination with an area of secondary shrinkage. The hole defect is indicative of liquid shrinkage and results from the use of a feeder neck which is too small and which freezes off before liquid contraction is complete. This situation is aggravated by the use of feeders which are too small and pouring temperatures which are too high.

**Situation E** - An area of secondary shrinkage is present under the riser neck, or closely adjacent to it. This is probably the most common feeding problem in ductile iron foundries. This area of secondary shrinkage occurs at a late stage of solidification and cannot be removed by additional feeding, because feeders only supply liquid metal in the early stages during liquid contraction. The problem can be caused by the use of a high pouring temperature or a small feeder, but is most often the result of using a feeder neck which is too large. This creates a hot spot which allows secondary contraction to occur at the neck/casting interface.

The ideal situation is to have a neck which freezes just before graphic expansion is complete, so that the majority of secondary contraction occurs on the feeder side of a frozen neck. In many cases this can be difficult to achieve by slight changes to the neck diameter, because of the influence of the many other variables, and in practice it is usually helpful to reposition the feeder or to remove it entirely.
5. Using riserless design

Many foundries are extremely reluctant to use riserless design in the production of ductile iron castings. The system is based on the concept of ensuring that certain important criteria are met, such that little or no liquid shrinkage occurs and the temperature distribution within the mould cavity is even, so that simultaneous solidification occurs without any 'hot spots'. For reasons related to temperature distribution, the production of riserless castings is usually related to chunky castings of greater than 25 mm modulus. There is no reason, however, why castings of lower modulus cannot be produced by this method provided that adequate chilling and densening is used to eliminate 'hot spots' and create an even temperature distribution. The use of metal chillers and chromite sand denseners or cores can often be more cost effective than the use of feeders, which reduce yield, can be costly to remove and which can generate scrap or expensive weld repair under the necks. The success of riserless production depends on the expansion that occurs on solidification due to the precipitation of graphite. This expansion must be at its maximum and it must be contained if the method is to be successful. The production criteria are therefore as follows:

1. The metal composition of the casting must be at the eutectic value of 4.25 C% to obtain maximum expansion.
2. Levels of carbide promoting elements must be low because the presence of carbide reduces expansion.
3. The pouring temperature must be below 1340°C and is usually in the range 1310-1330°C to minimise liquid shrinkage. In this low pouring temperature range solidification expansion will slightly exceed the liquid shrinkage that occurs.
4. The mould must be highly rigid. In practice this means well cured chemically bonded moulds which are in metal moulding boxes. Boxless moulds are less satisfactory, because although they can be adequately weighted they have a tendency to crack before solidification is complete and the solidification pressure is lost.
5. The mould should be poured fast through narrow ingates. The fast pour is to prevent mis-runs at the low temperatures being used and the narrow ingates are designed to freeze off quickly, so that the solidification expansion is contained.
6. Multiple narrow vents should completely penetrate the cope mould. These are to ensure a fast fill by preventing backpressure.
7. Where casting configuration is complex involving adjoining thin and thick sections, consideration should be given to local densening using chromite sand or metal chills.

Where foundries are unhappy about the use of riserless design or the production route does not enable the above criteria to be met, the pressure control risering technique developed for greensands can be used and has been found to be successful.

---

Fig. 1 Graphite flotation and dross stringers in a hypereutectic ductile iron.

Fig. 2 Dross stringers in a ductile iron of normal composition.
Fig. 3 "Ghost" structure in the position of a cast iron densene.

Fig. 4 Flake graphite rim on a ductile iron surface.

Fig. 5 Phosphorous segregation and associated shrinkage in a ductile iron.

Fig. 6 Dross pitting in the re-entrant corner of a heavy section ductile iron.
Fig. 7 Chunk graphite in a heavy section ductile iron.

Fig. 8 Phosphorous segregation and associated pearlite in the centre of a heavy section ferritic ductile iron.

Fig. 9 Comparison of ductile iron and steels during impact testing.

Fig. 10 Plate fracture at an ingate/casting junction.

Fig. 11 Nodule alignment associated with plate fracture.
Fig. 12 Good and bad pouring bush design.

Fig. 13 Typical shrinkage defects and their causes.

References
1. KASSAY S.
   Ductile iron 111 Gating and Risewing,
   QIT 1981 Canada (pages 3-50)
2. Dismatic Application,
   DISA, Dansk Industri Syndikat A/S, Denmark, page 65
3. WHEELDON J.B.
   'The Basic Causes of Shrinkage Defects in Ductile Iron Castings,'
   Institute of British Foundrymen Annual Conference, Harrogate,
4. ROEDTER H.
   An alternative method of pressure control feeding for ductile iron castings,

Figure References
Fig. 1 Graphite formation and dross stringers in a hyper-eutectic ductile iron.
Fig. 2 Dross stringers in a ductile iron of normal composition.
Fig. 3 "Ghost" structure in the position of a cast iron dendrite.
Fig. 4 Flake graphite rim on a ductile iron surface.
Fig. 5 Phosphorus segregation and associated shrinkage in a ductile iron.
Fig. 6 Dross pitting in the re-entrant corner of a heavy section ductile iron.
Fig. 7 Chock graphite in a heavy section ductile iron.
Fig. 8 Phosphorus segregation and associated porosity in the centre of a heavy section ferritic ductile iron.
Fig. 9 Comparison of ductile iron and steels during impact testing.
Fig. 10 Flute fracture at an ingate/casting junction.
Fig. 11 Nodular alignment associated with flute fracture.
Fig. 12 Good and bad pour bush designs.
Fig. 13 Typical shrinkage defects and their causes.