The effect of some foundry variables on dross formation in compacted graphite cast irons

by R. A. Harding

Synopsis—A study has been made of the effects of some foundry variables on the formation of dross defects in compacted graphite iron castings produced from metal treated with titanium and magnesium. Test castings have been examined visually to provide a qualitative assessment of the incidence of dross defects, and metallographically to determine the nature of the defects.

It has been established that dross defects can be reduced or eliminated by maintaining a high pouring-temperature, and adopting good foundry practice to prevent the transfer into the mould cavity of furnace slag and of reaction products resulting from the metal treatment. A ceramic filter inserted in the running-system was effective in preventing defects, when used to remove small amounts of dross from treated metal which had been correctly handled with thorough slag-removal prior to casting. The use of such filters is not an alternative to good foundry practice. Whether metal treatment was in the ladle or in the mould made no significant difference in the incidence of dross defects.

Variation in titanium content showed a slight effect; titanium should not exceed about 0.08 per cent.

Introduction—BCIRA has been advised by certain Member foundries that they have been experiencing severe dross defects during the manufacture of large castings in compacted graphite (CG) iron. These defects appear predominantly on the cope surfaces of the castings, and are usually revealed during a light machining operation to remove the casting skin. In certain instances, the occurrence of such defects has led to an unacceptably high scrap rate for the castings.

A recent review confirms that the formation of dross defects in nodular iron castings is by no means an uncommon occurrence. As a result of a large number of detailed studies, the metallurgical phenomena are relatively well understood and numerous practical guidelines for reducing or eliminating this defect have been recommended. However, CG irons are not so widely used as nodular irons, and although dross defects have been reported in the former they have not been studied in detail.

The research described in the present paper was carried out primarily to study aspects of the foundry process specific to the production of CG iron which increase or reduce the incidence of dross defects. Variables such as the mould composition (coal dust content, moisture content, and so on) and the gating and running system were not investigated, since results from previous work on nodular iron should be directly applicable to CG iron.

Investigation

Features common to all the melts carried out will first be discussed.

Moulds cast—The dross test-casting used in the present work was the same as that previously found suitable for a quantitative evaluation of the effects of process variables on dross defects in nodular irons. As shown in Fig. 1, this test-casting was a bottom-run block having nominal dimensions 152 × 138 × 38 mm, with a cylindrical feeder on the top face. The test-casting with the gating system shown in Fig. 1 was used for the first three melts. In subsequent melts, the system was modified as shown in Fig. 2 to incorporate a chamber for treatment with the magnesium alloy in the mould, and a second chamber for holding a ceramic filter.

The treatment chamber was designed by application of the recommendations of Dunks and co-workers, and was nominally 50 mm long, 28 mm wide and 25 mm deep. For treatments within the mould, the alloy used was crushed and graded to a size range of 1–2 mm. The filter chamber was based on design recommendations made by Fosco for the Sedex ceramic-foam filters. The filters were...
region of the fracture is shown in Fig. 10. No defects were present at the fracture face, but there was a cross-stringer adjacent to the fracture—penetrating the matrix to form a larger defective area beneath the cast surface.

The initiation of fatigue fractures beneath the surface is not unusual and can occur, for example, in the fatigue of case-hardened or nitrided steels where the combined tensile stress due to the applied fatigue stress and the residual stress associated with the case-hardening reach a maximum, usually at the transition zone between the case and the core material. The fractured specimen in Fig. 9 had a Tufftrided surface, and this may have contributed to the fracture initiation beneath the surface. However, the main cause is considered to be that the maximum stress in the fatigue test was beneath the cast surface owing to the presence of the defect in that area, which created a stress concentration promoting the fatigue crack before it started to propagate across the section.

Discussion

The results presented confirm findings of the earlier work, that when surface imperfections are present in the form of dross defects or flake graphite associated with dross, the fatigue limit may be reduced by about 20 per cent and possibly more—depending on the severity of the defect.

Many of the as-cast and Tufftrided fatigue specimens tested contained surface dross defects, and the results show that Tufftriding has limited the effect which these surface imperfections had on reducing the rotating-bending fatigue properties. When specimens with a fully machined, defect-free surface are compared with Tufftrided specimens containing surface dross defects, the reduction in fatigue limit is about 10 per cent rather than 20 per cent without treatment. Tufftriding treatments therefore appear to be a useful means of limiting the reduction in rotating-bending fatigue properties due to the presence of small castingsurface imperfections. Tufftriding will not restore the fatigue properties to the level obtained when the surface is completely free from defects.

Good control of moulding and metal treatment practice is required to produce nodular iron castings with cast surfaces free from surface imperfections such as dross and flake graphite associated with dross, or due to sulphur pickup from the mould. The earlier work showed that when imperfections were not present at the casting surface the fatigue properties were similar to those of fully machined, sound test bars. A Tufftriding or similar nitriding treatment carried out on a completely defect-free cast surface may well raise the fatigue properties above the level of fully machined test bars.

Conclusions

1 When imperfections are present at the cast surface their effect of reducing the rotating-bending fatigue properties of an as-cast pearlitic nodular iron may be limited by a nitrocarburizing heat treatment.

2 Small surface imperfections such as dross with associated flake graphite reduce the fatigue limit by about 20 per cent below that of fully machined, defect-free fatigue specimens.

3 In such conditions, a Tufftriding treatment reduces the loss in fatigue properties to 10 per cent.

REFERENCES


magnesium treatments were carried out within the mould, sections were taken from the dross test-castings for chemical analysis for silicon and magnesium and, where appropriate, titanium. The results of all the analyses are presented in Tables 3 & 4. The spectrographic analyses presented in Table 3 show that the carbon, manganese and sulphur contents were similar within and between melts. The trace elements, also given in Table 3, showed very small variations from melt to melt. The results of chemical or spectrographic analyses for silicon, magnesium, aluminium and titanium are collected together in Table 4 and will be discussed when individual melts are considered.

Pinnholes were present in some of the chill-cast spectrographic samples poured at temperatures below 1350 °C. In such cases, the analytical results are marked with an asterisk to indicate that the accuracy cannot be guaranteed.

**Evaluation of castings—** All castings were allowed to cool in the moulds to room temperature prior to knockout. They were then lightly shotblasted and examined for the presence of surface defects. Since previous work had established that a simple visual examination would not give a valid

| Table 2 Composition of alloys used for metal treatments. |
|---|---|---|---|---|---|
| Alloy No. | Treatment alloy | Mg | Si | Ca | Al | Ce | Ti |
| 1 | Mg-FeSi (5% Mg) | 4.99 | 4.48 | 0.64 | 0.75 | 0.09 | — |
| 2 | Low-Fe Ca-G alloy | 6.00 | 2.2 | 0.96 | 1.57 | — | 7.39 |
| 3 | High-Fe Ca-G alloy | 4.84 | 4.45 | 7.19 | 1.55 | — | 5.9 |

| Table 3 Composition of untreated metal determined spectrographically. |
|---|---|---|---|---|---|---|
| Melt | Composition % |
| | C | Mn | S | P | Al | Ca |
| 1 | 3.56-3.60 | 0.60-0.61 | 0.019 | | | |
| 2 | 3.56-3.58 | 0.61-0.63 | 0.017-0.024 | | | |
| 3 | 3.36-3.61 | 0.62-0.63 | 0.015-0.028 | | | |
| 4 | 3.63-3.64 | 0.65-0.67 | 0.016-0.017 | | | |
| 5 | 3.64-3.69 | 0.63-0.65 | 0.019 | | | |
| 6 | 3.48-3.58 | 0.65-0.68 | 0.016-0.018 | | | |
| 7 | 3.54-3.85 | 0.60-0.61 | 0.017-0.018 | | | |

*Results likely to have been affected by pinnholes in the sample.


For all melts: Ni 0.02-0.03%, Cr 0.03-0.04%, Cu 0.03-0.04, Mo 0.02%, Sn <0.01%, V <0.01%, B 0.0005-0.0008%, P 0.018-0.021%
Experimental melts and results

The experimental procedures and results for the seven melts carried out in the present work are now discussed individually. The metallographic examination of the defects is considered later, since the defects were similar in many of the castings examined.

**Melt 1**—To demonstrate the extent to which dross defects could form in compacted graphite irons as a result of deliberately poor foundry practice, and to determine how the severity of such defects might be influenced by variations in pouring temperature.

The 213 kg furnace charge was tapped at 1550 °C into a deep ladle, and a 0·1 per cent addition of titanium sheet was made to the metal stream. As shown in Table 4, the recovery of titanium was approximately 80 per cent, to give an iron containing about 0·08 per cent of this element. The top of the ladle was covered with a sheet of insulating material. Slag was allowed to remain on the surface of the metal. The metal temperature was continuously monitored by immersed thermocouple. At 50 °C intervals in the range from 1500 to 1300 °C, 25 kg of metal was tapped into a second ladle which contained a 1·2 per cent addition of magnesium-ferrosilicon (Alloy 1, Table 2).

No precautions were taken to prevent slag being transferred from the first ladle to the treatment ladle. When the reaction had subsided, one dross test-casting was poured, again without any attempt being made to prevent the entry of slag into the castings.

When the castings were cooling, it was noticed that a white deposit, as shown in Fig. 3, formed on the majority of the pouring-bushes and feeder heads. This deposit was

<table>
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<th>Silicon Final</th>
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</table>

*Results likely to have been affected by the presence of pinnacles in the sample.*

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powdery appearance but was tightly adherent to the metal, and its quantity generally increased as the pouring temperature decreased. Samples of the deposit were collected, and analysed by both X-ray diffraction and a scanning electron microscope. The details of these analyses are presented in the Appendix. It was concluded that the white deposit was rich in magnesium, and was probably magnesium oxide.

The machined top surfaces of the dross test-castings are shown in Fig. 4a, and the defects present in the casting poured at 1300 °C are shown in greater detail in Fig. 4b. It can be seen that with the exception of the casting poured at 1300 °C, all castings contained dross defects, and it was noted that these occurred predominantly at the end of the casting closest to the ingate. The incidence of these defects was particularly severe in castings poured from metal treated at temperatures of 1400 °C or lower. In the conditions used in these tests, the incidence of defects in the dross test-castings produced in compacted graphite iron were at least as severe as those found in earlier work with nodular graphite irons. Three out of the five castings contained shrinkage directly under the feeder head. This had been found in previous work, and should not be confused with the dross defect.

Microstructural examination of the castings showed that, with the exception of the casting poured at 1500 °C which had a flake graphite structure, all castings had a predominantly compacted graphite structure with a limited amount of nodular graphite. It is unclear why the graphite form was different in the castings poured at the higher temperature, since all the castings contained similar titanium and magnesium contents (Table 4).

From the observations made it was concluded that:

When foundry practice was poor with respect to the prevention of slag being transferred from one ladle to another, when reaction products were not removed by skimming, and when castings were poured without any attempt being made to prevent slag entering the castings, severe dross defects occurred in the compacted graphite iron castings.

Dross defects were formed when the magnesium-treatment temperature was lower than 1450 °C, corresponding to a pouring-temperature below 1420 °C.

3 The dross defects became more severe as the treatment and pouring temperatures decreased.

Melt 2—To demonstrate the extent to which dross defects could be reduced by good foundry practice.

To investigate the effects of small tellurium additions.

To confirm that the pouring temperature had a major influence on the occurrence of the defects.

The titanium and magnesium treatments were carried out in a similar way to those described for Melt 1. However, in contrast with the first melt, particular care was taken to remove dross from the surface of the metal prior to pouring. Furnace slag was removed before metal was tapped into the deep holding-ladle, which was of the teapot-spout type.
nodular iron, and therefore made it easier to prevent it from entering the mould.

The machined top surfaces of the dress test-castings poured without the tellurium addition are shown in Fig. 5a, and those with the tellurium addition in Fig. 5b. In comparison with the castings poured in Melt 1 (Fig. 4), it can be seen that the good foundry practice used in Melt 2 resulted in castings of much improved quality with relatively few, minor dross defects. In castings which had not been tellurium-treated, Fig. 5a, dross defects were only present when pouring followed magnesium treatment at 1300 °C. When the tellurium treatment was used, the dross defect appeared in castings when pouring followed magnesium treatment at 1400 °C or lower. It would therefore appear that, in contrast to previous work with nodular graphite irons, the addition of tellurium to compacted graphite irons was not beneficial and might even have slightly increased the incidence of dross defects.

In addition, metallographic observations summarized in Table 5 showed that there was a variation in the graphite form as a result of the tellurium addition, with some evidence to show that it had affected the formation of the required compacted graphite form.

Thus the results demonstrated that:
1. Good foundry practice significantly reduced the incidence of dross defects.
2. Although the incidence of dross defects was slight, they became more serious as treatment and pouring temperatures were reduced.
3. The use of a 0·005 per cent addition of tellurium failed to decrease the incidence of dross defects and had a detrimental influence on the graphite form.

Melt 3—To determine the extent to which a ceramic filter placed in the mould might be beneficial in reducing the incidence of dross defects caused by bad foundry practice.

The titanium and magnesium treatments were carried out under conditions of bad foundry practice as described previously for Melt 1. The running-system design was modified to incorporate a treatment chamber and a filter chamber (Fig. 2) although the magnesium treatment was not carried out in the mould in this melt. Pairs of moulds were poured, following a magnesium treatment in the ladle at 50 °C intervals in the 1500–1300 °C temperature range. Each pair of moulds consisted of one without a filter and one with a filter.

No attempt was made to remove the ladle dross formed during treatment at 1500 °C and 1450 °C. The mould containing a filter filled satisfactorily at 1500 °C but the filter blocked during pouring at 1450 °C, so a complete casting was not obtained. Therefore, before pouring of the remainder of the moulds (following magnesium treatment at 1400, 1350 and 1300 °C), most of the ladle dross was removed by skimming. This proved to be satisfactory for the mould poured at 1400 °C, but blocking of the filter still occurred for the moulds poured at 1350 and 1300 °C.

### Table 5: Analyses and structures produced, Melt 2.

<table>
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<th>Magnesium-treatment temperature, °C</th>
<th>Element %</th>
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The machined surfaces of the dross test-castings are shown in Fig. 6. The castings poured without a filter contained a considerable number of dross defects, and examination confirmed that the dross defects became worse as the pouring-temperature decreased. Since only two castings were successfully produced when a filter was used, definite conclusions could be drawn regarding the effects of the filters. There was, however, an indication that the moulds poured after magnesium treatment at 1450°C might further reduce the incidence of dross defects when some slag had already been removed from the metal surface. The blocking of filters experienced in the melt suggested that they should only be used for casting back five dross, after all reasonable steps had been taken to prevent its occurrence—by good foundry practice. The use of a filter was not a substitute for such good practice.

The results showed that:

- A ceramic filter placed in the running-system was not an alternative to good foundry practice to minimize the incidence of dross defects.
- There was limited evidence to suggest that a filter might be useful in further reducing the incidence of dross defects when these were already at a low level as a result of good practice.
- The dross defect became more severe as the treatment and pouring temperatures were reduced within the range 1500–1300°C.

![Machined cope surfaces of dross test-castings, Melt 3.](image)

**Fig. 6** Machined cope surfaces of dross test-castings, Melt 3.

**Treatment temperatures (from left to right):** 1500, 1450, 1400, 1350, 1300°C.

**Top row:** Castings poured without a filter.

**Bottom row:** Castings poured with a ceramic-foam filter in the running-system.

Alloy used was the same as that used for previous melts (Alloy 1, Table 2) but was crushed and graded to 1–2 mm. Two moulds were poured at each temperature, one without a filter and one with a filter in the running-system.

It was found that full solution of the magnesium treatment alloy occurred at the two higher pouring temperatures of 1490 and 1435°C. Dissolution was

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**Table 6: Effect of a running-system filter on the pick-up of Si and Mg during treatment in the mould in Melt 4.**

<table>
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<th>Temp.</th>
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<th>Filter</th>
<th>Silicon Initial %</th>
<th>Silicon Final %</th>
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<th>Magnesium final %</th>
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* Spectrographic analysis
* Chemical analysis
N.A. Not available
Estimate
probably incomplete when pouring temperatures were 1395 °C, and was definitely incomplete when pouring was at 1350 and 1300 °C.

The silicon and magnesium contents of the dross test-castings were determined by chemical analysis, and the results are presented in Table 6. Comparison of results for moulds poured without and with a filter showed that the presence of a filter had no significant effect on the pick-up of these two elements during the treatment process. The magnesium pick-up could be considered as being consistent within the range 0.017–0.020 per cent when moulds were poured at between 1500 and 1400 °C, slightly lower at 0.016 per cent when pouring was at 1350 °C, and significantly lower at 0.010–0.012 per cent with pouring at 1300 °C. On the other hand, the pick-up of silicon varied more gradually with the different pouring-temperatures. The results of the chemical analysis therefore agreed with the observations noted above regarding the dissolution of the magnesium treatment alloy.

The machined top surfaces of the dross-test castings poured without and with a filter are shown in Figs. 7a & b respectively. It can be seen that all the castings were free from major dross defects. This was in marked contrast to castings produced in previous melts, with the exception of those in which good foundry practice had been used. Three possible reasons can be put forward for this improvement in casting quality:

1 A considerable delay occurred between making and pouring of the moulds. This was during a period of hot weather which probably reduced the mould moisture content to a lower level than that for previous melts. Other work has shown that dross defects in nodular iron decreased as the moisture content of greensand moulds decreased, and it is possible that the drier moulds used in this melt for compacted graphite iron might have accounted for the absence of dross defects.

2 As already noted, a low residual titanium content was obtained in this melt. It was considered that this might have contributed to the marked reduction of dross defects. In view of the possible importance of the titanium content, Melt 6 (which is described later) was carried out, to investigate the effects of increasing titanium contents.

3 It is generally accepted that treatment in the mould improves the magnesium recovery and therefore reduces the amount of magnesium required, and hence the likelihood of dross defects. Furthermore, the amount of oxidation both during and after the magnesium treatment might be less.

Subsequent melts indicated that explanations (2) and (3) were probably of minor importance, and it was concluded that the drier moulds used for this melt were primarily responsible for the observed reduction in dross.

Since castings poured without a filter contained no major dross defects, no real benefit of using a filter could be established in the present work. However, it was noted that the casting poured at 1300 °C without a filter contained heterogeneities which appeared as bright spots (Fig. 7c), whereas the equivalent casting poured with a filter was more homogeneous.

As will be shown later, these bright spots were found to be small areas of dross stringers with associated nodular or compacted graphite in an otherwise flake graphite iron.

Metallographic examination was carried out, to determine the graphite form, its relation with the titanium and magnesium contents, and the effect of filtration on
Metal cleanliness. With treatments at 1395 °C and below, the structure consisted of predominantly compacted graphite but also contained a small number of graphite nodules. At treatment temperatures of 1350 °C and below, graphite was mostly in a flake form. However, there were also isolated areas of nodular and compacted graphite associated with dross stringers, and these were particularly prevalent in castings poured without a filter. From these observations and the analyses (Table 5), it was concluded that, with a low titanium content of approximately 0·025 per cent, a changeover from compacted to flake graphite occurred as the magnesium content fell from 0·018 to 0·016 per cent.

It was also observed that castings poured with a filter tended to have far fewer dross stringers than equivalent castings poured without a filter. It was concluded that a filter could improve the metal cleanliness but could not guarantee the absence of dross defects.

The results demonstrated that:

1. There was evidence to suggest that the drying-out of moulds might reduce the incidence of dross defects.
2. The presence of a ceramic filter could reduce the incidence of dross stringers.

**Melt 5**—To repeat Melt 4 using higher titanium contents, and to determine the incidence of dross defects following treatment in the mould at various temperatures with and without a filter.

The titanium was added to the metal stream at an early stage during tapping of the metal from the furnace into the ladle. The analyses (Table 4) show that, in contrast with Melt 4, a recovery of about 80 per cent was obtained to give a satisfactory titanium content. Five taps of 30 kg were taken at nominally 50 °C intervals in the range 1500–1300 °C, and were used to pour two dross test-castings employing magnesium treatment in the mould with and without a filter.

Chemical analysis for magnesium (Table 4) showed that, with the exception of Moulds 9 & 10 poured at 1300 °C, a satisfactory magnesium content of about 0·02 per cent was obtained.

The machined surfaces of the dross test-castings poured without and with a filter are shown in Figs. 8a & b respectively. Fig. 8a shows that the dross defects in castings poured without a filter generally became progressively more severe as the pouring-temperature decreased, although it was noted that the casting poured at 1300 °C did not follow this general trend. Fig. 8b shows that the use of a filter in the running-system beyond the treatment chamber led to a significant reduction in the incidence of dross defects, although these defects were not completely eliminated.

Comparison of the dross test-castings poured without a filter in the present melt with castings poured without filters in previous melts allowed the following tentative conclusions to be drawn:

1. Magnesium treatment in the mould might result in more dross defects than ladle treatment carried out with good foundry practices (comparison of Figs. 8a & 5a).
2. On the other hand, treatment in the mould might result in less dross defects than ladle treatment employed with (deliberately) poor foundry practices (comparison of Figs. 8a & 4a).
3. A titanium content of 0·025 per cent might result in less dross defects than a titanium content of 0·08 per cent (comparison of Figs. 7a & 8a).

Metallographic examination showed that all castings produced from metal poured at 1350 °C and above had a predominantly compacted graphite structure containing small amounts of nodular graphite. These observations, together with the analyses given in Table 4, suggested that a magnesium content in excess of 0·020 per cent would ensure a compacted graphite structure when the titanium content was of the order of 0·08 per cent. In contrast, the castings poured at 1300 °C had a predominantly flake graphite structure, which suggested that a magnesium content of 0·014 per cent was too low to ensure a compacted graphite structure when the titanium content was 0·08 per cent.

During this part of the work, it was concluded that:
1. Dross defects were formed when compacted graphite irons were produced by magnesium treatment, within the mould, of titanium-containing irons.
2. A ceramic filter inserted in the running-system was effective in reducing the severity of dross defects in irons produced in this way.
3. The titanium content of CG irons may influence the severity of dross defects.

**Melt 6**—To examine further the effect of titanium content on the severity of the dross defect in CG irons produced by magnesium treatment within the mould, with and without a filter in the running system.

The base iron was produced as in previous melts and, when molten, was held at 1550 °C under an argon cover.

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**Fig. 8** Machined cope surfaces of dross test-castings, **Melt 5:** (a) without a filter, (b) with a filter in the running-system.
Five 30 kg taps were taken with different additions of titanium made during the tap, as shown in the following table.

**Additions and recovery of titanium during Melt 6.**

<table>
<thead>
<tr>
<th>Tap</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ti addition made %</td>
<td>0</td>
<td>0.05</td>
<td>0.10</td>
<td>0.15</td>
<td>0.20</td>
</tr>
<tr>
<td>Ti content of metal %</td>
<td>&lt;0.01</td>
<td>0.037</td>
<td>0.079</td>
<td>0.105</td>
<td>0.141</td>
</tr>
<tr>
<td>Recovery %</td>
<td>74.0</td>
<td>79.0</td>
<td>70.0</td>
<td>70.5</td>
<td></td>
</tr>
</tbody>
</table>

The titanium recovery was reasonably consistent, and was within the range 70–80 per cent.

The temperature of each ladle of titanium-treated metal was measured and, once it had dropped to 1400 °C, two dress test-castings were poured, one without a filter and one with a filter. The magnesium treatment was carried out within the mould cavity, as described for the preceding melts.

The chemical analyses reported in Table 4 showed that the recovery of magnesium during treatment was consistent, and gave contents between 0.017 and 0.020 per cent. Likewise, the silicon contents of the treated metal were consistent within the range 2.15 to 2.18 per cent.

The machined surfaces of the dress test-castings poured without and with a filter in the running-system are shown in Figs. 9a & b respectively. It can be seen from Fig. 9a that all the test castings poured without a filter contained dress defects. The titanium content had no major effect on the severity of the dress defect, although the casting with the highest titanium content, of 0.14 per cent, did show a tendency towards more numerous defects.

When a filter was used in the running-system, Fig. 9b, the incidence of dress defects was significantly reduced. No dress defects were visible at the machined surface when the titanium content was less than 0.079 per cent, and only minor defects were seen in the castings containing 0.105 and 0.141 per cent titanium. This confirms the beneficial action of a filter, as found in the previous melt.

The examination of the castings produced in this melt provided confirmation that magnesium treatment within the mould reduced the incidence of dress defects to levels much lower than those which occurred after ladle treatment combined with deliberately bad foundry practice. On the other hand, with good foundry practice following ladle treatment, the incidence of dress defects was probably less than that occurring with treatment in the mould.

Metallographic examination showed that the castings produced without a titanium addition had a very variable graphite structure, containing areas of flake, compacted and spheroidal graphite. The remaining castings which contained 0.037 per cent or more of titanium all had a predominantly compacted graphite structure with a small proportion of graphite nodules. These observations, together with the analyses (Table 4) therefore suggested that, when magnesium treatment was carried out in the mould to give a magnesium content of 0.017–0.020 per cent, a titanium content as low as 0.04 per cent was sufficient to produce a satisfactory compacted graphite structure.

Therefore, the results showed that:
1. A variation of the titanium content between <0.01 per cent and 0.141 per cent had only a minor effect on the severity of dress defects found in CG irons containing approximately 0.02 per cent magnesium.
2. A ceramic filter inserted in the running-system was highly effective in reducing the incidence of dress defects in irons treated within the mould.

**Melt 7—To determine the incidence of dress defects when treatment to produce compacted graphite structures uses a CG alloy addition, either to the ladle or within the mould.**

The iron was melted as described previously, and held under an argon cover at 1500 °C. Two 15 kg taps were taken and allowed to cool in a ladle to 1400 °C. One dress test-casting was poured from each tap, treatment being carried out in the mould with either a low-calcium CG alloy (Alloy 2, Table 2) or a high-calcium CG alloy (Alloy 3, Table 2). These alloys were crushed and graded to a size of 1–2 mm. Two further 15 kg taps were taken, allowed to cool to 1450 °C, and then tapped onto a 1 per cent addition of either low- or high-calcium CG alloy in a second ladle fitted with a tundish cover. After stirring to ensure complete dissolution of the alloy and skimming to remove the dress, one mould was poured from each ladle at a nominal temperature of 1400 °C.

The treatments carried out are summarized below:

**Treatments in Melt 7.**

<table>
<thead>
<tr>
<th>Tap</th>
<th>Treatment</th>
<th>CG alloy</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Mould</td>
<td>Low-Ca</td>
</tr>
<tr>
<td>2</td>
<td>Mould</td>
<td>High-Ca</td>
</tr>
<tr>
<td>3</td>
<td>Ladle</td>
<td>Low-Ca</td>
</tr>
<tr>
<td>4</td>
<td>Ladle</td>
<td>High-Ca</td>
</tr>
</tbody>
</table>
obtained was too high relative to the titanium content. A CG alloy containing approximately 3 per cent magnesium for treatments within the mould is available, but this was not used in the present work. Also, in normal production, returns would be used to give a base iron containing approximately 0.04 per cent titanium. This is taken into account in the formulation of the CG alloys, and it suggested that if the base iron used in the present work had contained 0.04 per cent titanium, satisfactory compacted graphite structures would probably have been obtained.

In Tap 2, the low reactivity of the high-calcium alloy led to a low magnesium recovery, which in turn led to a flake graphite structure. Although increasing the size of the treatment chamber could have brought about a more satisfactory structure, it is unlikely that this would be feasible in practice.

The compacted graphite form in both ladle-treated castings (Taps 3 & 4) was satisfactory, as would be expected from the recoveries of magnesium and titanium obtained.

The machined cast test castings are shown in Fig. 10. It can be seen that the two castings treated within the mould were essentially free from flake defects, whereas the two castings poured from ladle-treated metal contained a larger number of flake defects. Direct comparison of these results is difficult, owing to the different titanium and magnesium contents of each casting (Table 4). However, evidence was obtained from Melt 6 that the titanium content had no major influence on flake morphology and, on this basis, it was possible to conclude that:

1. Treatment within the mould resulted in fewer flake defects than treatment in the ladle.
2. In ladle treatments, a low-calcium CG alloy produced fewer flake defects than a high-calcium CG alloy.

Metallographic examination of flake defects
As already noted, the defects found in castings produced in different melts were often similar in nature, so they are now discussed without reference to specific melts.

Severe flake defects—Severe flake defects were defined as those which were readily visible on a machined surface and usually had the appearance of irregular blow-holes. Sections taken through such defects usually revealed them to be lined with a two-phase layer, as shown typically in Figs. 11, 12a & 12b. It is suggested that the two-phase layer consists...
predominantly of magnesium reaction products, particularly oxides and sulphides, which enter the mould and react with carbon contained in the melt to give carbon monoxide. The generation of the latter gives rise to the characteristic blow-hole formation shown in Fig. 12a. However, it should also be noted that large particles of dross not accompanied by blow-hole defects were also found, as shown typically in Figs. 13 & 14. It can be seen that the nature of the dross shown in Fig. 11 is different from that shown in Figs. 13 & 14, and this would suggest that they might have different chemical compositions. No attempt was made to analyse these drosses; however, a recent review has shown\(^1\) that a large number of different constituents can be found in drosses formed during nodular iron production, including magnesium oxides, sulphides and silicates, and oxides of iron, calcium and aluminium, and it is expected that the drosses formed during CG iron production would be similar.

A limited number of blow-hole defects were also found, which were characterized by a smooth uniform internal surface, with a graphite rim adjacent to the decarburized metal (Fig. 15). These were identified as being pinholes formed by hydrogen during solidification, and are usually caused by an excessive amount of aluminium in the iron due to impure charge materials or excessive aluminium in the treatment alloys.
Fig. 16 Undissolved treatment alloy surrounded by dross stringer (Melt 1, Mould 5); etched in 4% picral. x 50

Dross stringers—Many of the castings examined contained fine stringers of dross which often penetrated deep into a casting, but were not necessarily visible at the machined surface. Fig. 16 shows a particle of undissolved treatment alloy enveloped by a dross stringer, whereas Fig. 17 shows a dross stringer associated with an area containing some nodular graphite and carbides. The increased amount of nodular graphite which was often associated with dross stringers is shown well in Fig. 18, and was found to be responsible for the bright spots on the machined surface of a casting with an otherwise flake graphite structure (Fig. 7c).

Inclusions—Some castings were found to contain large numbers of fine inclusions, either distributed uniformly or concentrated in localised areas. Fig. 19(a) shows a representative example of uniformly distributed inclusions.

Fig. 18 Dross stringers and associated areas of nodules (Melt 4, Mould 9); etched in 4% picral. x 50

and Fig. 19(b) shows one area at a higher magnification. Two types of inclusion predominated: very fine, dark-grey graphite inclusions; and angular, pinkish-grey inclusions which remained proud on a polished surface and were identified as being titanium cyanonitride, Ti(C,N). In some

Fig. 17 Dross stringers and associated areas of nodules and carbide (Melt 1, Mould 5); etched in 4% picral. x 50

Fig. 19 Fine graphite particles and titanium cyanonitride inclusions (Melt 2, Mould 7); etched in 4% picral. (a) x 50, (b) x 500
casings, concentrations of very fine titanium cyanonitride inclusions were found in localized areas (Fig. 20), suggesting that the titanium had not dissolved uniformly. As would be expected, the occurrence of titanium cyanonitride inclusions increased as the titanium content increased. There was no evidence to suggest that these inclusions were concentrated near the large gross defects, although there were occasionally higher concentrations near the filamentary gross stringers.

Discussion

The present work has confirmed industrial experience, that CG iron castings may be subject to the formation of gross defects and that the defects are most prevalent on the cope surface of castings.

Although CG irons can be produced by the addition of nitrogen to the base metal, or by the cerium treatment of low-sulphur irons, the majority of CG irons are made by treatment of the iron with 0.08 - 0.15 per cent titanium and 0.015 - 0.035 per cent magnesium. These additions can be made either separately or simultaneously by use of a specially formulated treatment alloy. When magnesium is used, it is considered that the mechanisms of gross formation in CG iron are likely to be similar to those in nodular irons. In the latter, gross defects can arise from:

- the products formed during the magnesium treatment which are subsequently transferred with the molten metal from the ladle into the mould cavity;
- the products formed by the oxidation of magnesium and other elements such as silicon and aluminium during the holding period in the ladle, during the flow of metal into the mould and prior to solidification of the casting;
- oxidation resulting from contact between the molten metal and the moulding-sand, particularly when the latter contains excessive moisture or insufficient carbonaceous matter to generate a reducing atmosphere.

In the present work, it seems that most of the gross defects occurred as the result of the transfer of magnesium reaction products from the ladle to the mould cavity. Support for this conclusion is found in the fact that the incidence of gross defects was markedly reduced when good ladle practices were used and when a ceramic filter was included in the running-system. Nevertheless, even when a filter was used, some test castings contained a few large gross defects, and most contained some gross stringers. No conclusion can be drawn, whether these defects were due to gross particles not being retained by the filter, or were due to the formation of gross in the metal once it had passed through the filter.

The melts described in the present paper have shown clearly that the severity of gross defects increased as the magnesium-treatment temperature (and hence the pouring-temperature) decreased in the range 1500 - 1300 °C. Castings treated at or below 1450 °C were susceptible to gross defects, whereas those treated at higher temperatures were generally free from such defects. This agrees with previous work at BCIRA and elsewhere on gross formation in nodular iron. It has been suggested that, at temperatures greater than 1480 °C, oxygen reacts with carbon dissolved in the iron to form carbon monoxide rather than with magnesium to form gross. However, as the temperature drops oxidation of silicon occurs, to combine with products of the magnesium reaction and lead to gross formation. Heine & Loper have suggested that during the continuous cooling of a bath of nodular iron the surface of the molten metal remains free from gross until temperature of about 1450 °C is reached, and that this is the result of a protective magnesium-vapour blanket being formed over the metal. As the temperature falls below 1450 °C, a slag film is formed in increasing amounts until, at 1350 °C, the slag becomes crusty and a solid gross forms.

It is therefore beneficial to use a pouring-temperature which is as high as possible. However, since high temperatures may be difficult to maintain, may seriously reduce the magnesium recovery, or may lead to increased unsoundness, it is clear that other factors responsible for gross formation should also be considered.

The present work has shown that it is essential to ensure good ladle practice, including the careful skimming of the top of the ladle prior to pouring, and particularly the use of a teapot-spout ladle. Assuming that these recommendations are followed, the prevention of gross defects can be assisted by the use of a ceramic filter placed in the running-system. However, a ceramic filter can only retain a limited amount of gross before it blocks and prevents filling of the casting; a filter is not a substitute for good foundry practice.

Previous work at BCIRA has shown that the addition of 0.005 per cent tellurium to a magnesium-treated nodular iron reduced the fluidity of the slag and changed it to a 'chunky' form which was easier to remove. When this addition was made to compacted graphite iron no benefit was gained. Furthermore, the tellurium had an adverse effect on the graphite form, although this might have been prevented by the presence of cerium.

A melt was carried out to determine whether the incidence of the gross defect depended on the titanium content of compacted graphite irons. The results suggested that defects increased at high titanium contents—probably of the order of 0.08 per cent or more. However, in comparison with the effects of good versus bad ladle practice, those of titanium were relatively minor. One noticeable feature of the present work was the tendency for gross defects in compacted graphite irons to be relatively high, for the low residual-magnesium contents used. This might indicate that the presence of titanium contributed to the formation of gross defects, even though variations in its content had relatively small effects.

The influence of the residual-magnesium content was not studied in the present work. Previous work at BCIRA demonstrated that the residual-magnesium content was the most important single factor influencing the incidence of...
Appendix: Examination of white deposit found on the surface of compacted graphite iron castings

**Scanning electron microscopy:**
Samples of the white deposit were collected from the pouring-bushes of moulds poured in Melt 1 and, after mounting and polishing, were examined in a scanning electron microscope fitted with an energy-dispersive spectrometer. In the area examined (Fig. A1), three constituents were detected and found to be a magnesium-rich white powder (Fig. A2), silicon-rich sand grains (Fig. A3) and particles of iron (Fig. A4).

**X-ray diffraction:**
Similar samples to those above were subjected to X-ray diffraction analysis from which it was established that the white deposit was magnesium oxide (MgO), with no other constituents present in measureable quantities.

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Fig. A1 Secondary electron image of debris collected from pouring-bush of CG iron (Melt 1). \( \times 20 \)

Fig. A2 EDA distribution of magnesium within the area shown in Fig. A1. \( \times 20 \)
dross defects in nodular iron, whereas Heine & Loper\textsuperscript{10} suggested that a low magnesium content was of little value in preventing dross defects. A recent American study\textsuperscript{1} has concluded that increasing the magnesium content led to only a slight increase in dross in nodular iron, particularly when greensand moulds were used. It is suggested that good-quality CG iron castings can be obtained if the normally recommended magnesium contents for this type of iron are maintained, with the proviso that good foundry practices must always be used.

In the present work, a comparison has been made between treatments to produce compacted graphite iron in the mould or in the ladle. The former led to fewer dross defects being formed although in both cases, with good ladle practice, the incidence of defects was low. However, treatment in the mould to reduce the incidence of dross defects depends also upon the maintenance of good ladle and slag-removal practices before the casting is poured. On the basis of the present work, no clear preference can be put forward for either treatment (in the ladle or in the mould) since it has been shown that both are capable of producing good-quality castings.

In addition to the factors discussed above, there are several important considerations which influence dross formation in ductile irons and should be equally applicable to CG irons:

A pouring-basin and tapered sprue reduce the entrainment of air and mould gases in the metal stream by preventing vortex formation and separation of the metal from the sides of the sprue.\textsuperscript{2}

The gating system should be designed to supply iron rapidly and with a minimum of turbulence. A positive-pressure system of 4:8:3 has been recommended,\textsuperscript{1} since the low metal velocity in the large runner provides minimum turbulence and maximum dross entrainment.

The mould material can influence dross formation, and various ratings have been proposed.\textsuperscript{1-3} Greensand moulds are suitable if high moisture contents are avoided and if the coalust content is maintained at about 6 per cent.

The sulphur content of the metal before treatment should be as low as possible.\textsuperscript{1-3} The aluminium content should be less than 0.01 per cent, controlled by the careful choice of raw materials.\textsuperscript{1}

**Recommendations**

Findings of the present investigation suggest that the following steps should be taken to reduce or eliminate the occurrence of dross defects in CG iron castings:

1. The pouring-temperature should be kept as high as possible, preferably above 1400 °C, assuming that this does not lead to too low a magnesium recovery or create other problems—such as shrinkage.

2. Particular care should be taken to remove the reaction products formed during metal treatment in the ladle, prior to pouring castings.

3. The use of a teapot-spout ladle is strongly recommended, to reduce the possibility of transfer of dross from the ladle to the mould cavity.

4. The inclusion of a ceramic filter in the running-system has been found to be extremely effective in removing small amounts of dross inadvertently transferred from the ladle. However, a filter should not be used to counteract bad ladle practice; it will become blocked if too much slag is present in the metal stream.

5. If it is not possible to incorporate a ceramic filter in the running-system, a whirlgate should be used and the running-system redesigned to promote the separation of slag from the treated iron and to create non-turbulent conditions in the metal stream.

6. The titanium and magnesium contents should be kept as low as possible within the range required to obtain a good compacted graphite structure.

7. Steps should be taken to ensure that the moulding and gating systems conform to the recommendations previously established\textsuperscript{1-3} for nodular irons.

**Conclusions**

1. This investigation has confirmed industrial experience that compacted graphite iron castings can be susceptible to the formation of dross defects.

2. Dross defects are caused primarily by the transfer of products formed by the magnesium treatment, from the ladle to the mould cavity. They can be reduced significantly by the application of good foundry practice to ensure that, first, that furnace slag and reaction products are skimmed from the surface of the treated metal before it is poured, and by the use of a teapot-spout ladle for pouring.

3. The incidence of dross defects increases as the pouring-temperature decreases within the range 1500 to 1300 °C. Maintaining the pouring-temperature above 1400 °C can substantially reduce defects.

4. If good foundry practice is applied, the limited incidence of dross defects can be further reduced by the use of a ceramic filter in the running-system. The use of a filter is not an alternative to good foundry practice.

5. Variations in the titanium content have only a minor effect on the formation of dross defects. It is recommended that this element should not exceed approximately 0.08 per cent.

6. When good foundry practices are adopted, the incidence of dross defects is not significantly affected by whether metal treatment to produce a compacted graphite structure is carried out in the mould rather than in the ladle.

**REFERENCES**


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