Ferrite in shell-moulded grey iron castings—
a summary paper

by P. J. Rickards

Synopsis—Ferrite in considerable quantity often occurs in shell-moulded grey iron castings, particularly near their cast surfaces, and this causes low surface-hardness values, a poor machined finish and incorrect casting-quality assessment. Most of this ferrite forms from austenite, on cooling through the eutectoid temperature range, but in addition there is sometimes a well-defined ferritic surface rim, and this originates from surface decarburization at temperatures above the eutectoid.

It has been shown that the quantity of ferrite can be reduced—by keeping the carbon and silicon contents of the iron as low as possible, by controlling the manganese: sulphur ratio of the iron, and by ensuring use of the most efficient inoculation practice. Backing the shell mould, or using mould washes or metal additions, or controlling the shell-mould thickness are further ways of reducing the ferrite content of shell-moulded castings.

The occurrence of ferrite
A study of castings of widely differing sizes and shapes, from many foundries, has shown that large quantities of ferrite often occur in grey iron castings made in shell moulds. The ferrite is concentrated near the casting surfaces and is usually associated with local areas of fine graphite. (This ferrite is referred to as 'general' ferrite throughout the present work). In addition, there is sometimes a sharply defined ferritic rim in the immediate surface zone. These distinctly different forms of ferrite are illustrated in Figs. 1 & 2. Ferrite in grey iron castings can be the cause of: low surface-hardness values; impaired load-bearing capacity; reduced wear-resistance in service; difficulties in casting-quality assessment by measurement of surface hardness; and a poor machined finish if the tool vibrates. It can also be detrimental if castings are to be surface hardened.

The surface structures of grey iron castings are becoming increasingly important because users may specify that the castings should have fully pearlitic structures right up to the cast surfaces, or that the surface structures should have less than a given proportion of ferrite.

Producers of shell-moulded castings are aware that such castings are prone to the formation of ferrite, and small additions of tin, antimony, arsenic, copper or chromium may be made to the metal in attempts to suppress the ferrite. However, these elements are costly, and they can build up to levels which might cause a significant deterioration in mechanical properties.

There is little published information concerning the occurrence of ferrite in shell-moulded grey iron castings. Morey & others and Ames have studied the heat-transfer characteristics of castings made in shell moulds. Although these authors mainly
considered non-ferrous castings, some work was carried out using nodular graphite (SG) irons. No results were given for unbacked shell moulds, and cooling rates were only considered down to a temperature of 1100 °C. It seems probable, however, that variations in the rate of cooling will influence the quantity of ferrite occurring in shell-moulded grey iron castings.

The formation of ferrite, and the effect of metallurgical and mould variables on the extent to which it occurs in shell-moulded grey iron castings, have recently been examined by Rickards. The use of mould-backing materials, and other possible methods of suppressing ferrite, have also been described. The present paper summarizes the factors influencing the formation of ferrite in shell-moulded castings, and suggests methods for its suppression.

**Formation of ferrite**

Previous results, obtained by Morey & others, suggest that as a casting cools in a shell mould it is subjected to a definite sequence of cooling-rate changes and these are fundamental to the shell-moulding process. Initially, rapid cooling is induced by the mould; but once the mould begins to break down to form a thermally insulating layer on the casting surface, there is a marked decrease in the cooling rate. Finally, if the burnt-sand residue falls away from the casting surface, the rate of cooling will increase again. The extent to which ferrite occurs in a shell-moulded grey iron casting is determined by the temperature ranges through which these changes in the cooling-rate occur, and the rate of cooling is determined by the mass of the casting in relation to the thermal capacity of the shell mould.

To ascertain at what stage the ferrite formed, shell-moulded castings of 13 mm (1 in) section have been water-quenched as they cooled through the eutectoid temperature range. The results showed that the general ferrite formed in a different manner from ferrite which occurs as a continuous rim in the immediate surface zone.

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**Fig. 1** Microstructure up to the surface of a small shell-moulded chain casting, showing general ferrite associated with areas of fine graphite. Etched in 4% picral. × 60.

**Fig. 2** Microstructure showing a ferritic rim in a shell-moulded grey iron casting. Etched in 4% picral. × 60.

**Fig. 3** Microstructure of a casting water-quenched from 715 °C shell-mould surface uncovered; showing ferrite forming in local areas of fine graphite, completely surrounded by martensite. Etched in 4% picral. × 60.

**General ferrite**—Most of the ferrite associated with fine graphite formed from austenite during the eutectoid transformation. This was indicated by the observation that the developing ferrite was completely surrounded by martensite in a casting quenched from 715 °C, (Fig. 3).

**Ferrite rim**—The ferritic rim began to form at temperatures of about 800 °C—that is, well above the eutectoid temperature. The pro-eutectoid nature of the ferrite, the well-defined boundary between the ferritic rim and the general matrix structure (Fig. 2), and the presence of an oxide layer whenever the rim was formed, led to the conclusion that surface decarburization at temperatures between the eutectic and the eutectoid
Fig. 4. Microstructure of casting quenched from 740 °C, shell-mould surface backed on moist sand; showing ferrite forming in immediate surface zone. Etched in 4% picral. ×200.

Fig. 5. Surface microstructure of a casting of 10 mm (⅜ in) section, shell-mould surface uncovered; containing 1.64% silicon; surface hardness HB210. Etched in 4% picral. ×60.

Fig. 6. Surface microstructure of a 10 mm (⅜ in) section casting, shell-mould surface uncovered, containing 2.58% silicon; surface hardness HB 162. Etched in 4% picral. ×60.

was responsible for the formation of this rim. The microstructure in Fig. 4 shows developing rim in a casting quenched from 740 °C.

Factors influencing the formation of general ferrite

Chemical composition—Raising the carbon or silicon content of the iron increased the quantity of ferrite and there was a corresponding decrease in surface hardness, as shown by the results in Table I and Figs. 5 & 6. Silicon had a much greater effect in promoting ferrite near the cast surface than it did in the centre of the casting.

The results in Fig. 7 show that to obtain the minimum quantity of ferrite, the manganese and sulphur contents of the iron should be accurately balanced according to the formula \( \% \text{Mn} = 1.7 \times \% \text{S} \); alternatively, the manganese content should be about 1 per cent in excess of that required to balance

![Graph showing relationship between Mn:S ratio and surface hardness](image)

**Fig. 7 Relationship between the Mn:S ratio and the surface hardness of shell-moulded castings—13 mm (⅜ in) section.**

**Table 1 Effect of carbon content of the iron, and of pouring temperature, on the surface hardness of 1:1 mm (⅜ in) shell-moulded castings.**

<table>
<thead>
<tr>
<th>Carbon content of iron</th>
<th>Pouring temperature, 1400 °C</th>
<th>Pouring temperature, 1329 °C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mould surface uncovered</td>
<td>Mould surface backed by moist sand</td>
</tr>
<tr>
<td>%</td>
<td>186</td>
<td>210</td>
</tr>
<tr>
<td>3.29</td>
<td>168</td>
<td>191</td>
</tr>
</tbody>
</table>

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the sulphur, to achieve surface hardnesses typical of fully pearlitic castings. A small excess of manganese—of 0-2 to 0-3 per cent—which is often used in grey iron foundries, promoted the greatest quantities of ferrite and the lowest surface hardness (Fig. 7).

Gas content of the metal.—When hydrogen was introduced into the melt, by means of a moist-sand lance, the quantity of general ferrite was reduced¹. Figs. 8 & 9 show that there was little visible change in graphite fineness to account for the effect of hydrogen.

It is well-known that aluminium increases hydrogen pick-up, and it might be anticipated therefore that small amounts of aluminium would reduce the quantity of ferrite. However, additions of 0-02–0-05 per cent aluminium have been shown to have no significant effect on the quantity of ferrite or surface hardness².

Irons having various nitrogen contents were made with steel-based charges, using a low- and a high-nitrogen recaurizer. The results, in Table 2, show that there was a small decrease in the quantity of ferrite and an increase in surface hardness when the high-nitrogen recaurizer was used.

Inoculation.—Although inoculation often reduced the quantity of ferrite by promoting a more uniform graphite structure, it by no means completely eliminated it, as shown in Figs. 10 & 11.

Table 2 Effect of the nitrogen content of the iron on the quantity of ferrite & surface hardness of castings of 13 mm (½ in) section.

<table>
<thead>
<tr>
<th>Carburizer &amp; treatment</th>
<th>Metal nitrogen content (ppm)</th>
<th>% ferrite in surface 1-3 mm (0-05 in)</th>
<th>Depth to which ferrite occurs x mm (x 10⁶ in)</th>
<th>Surface hardness HB 6/750</th>
</tr>
</thead>
<tbody>
<tr>
<td>Graphite</td>
<td>50</td>
<td>40</td>
<td>2.6 (100)</td>
<td>181</td>
</tr>
<tr>
<td>Carbon 99</td>
<td>120</td>
<td>35</td>
<td>2.6 (95)</td>
<td>197</td>
</tr>
</tbody>
</table>

Fig. 8 Microstructure up to the surface of a 10 mm (½ in) casting; no hydrogen treatment. Etched in 4% picral. ×50.

Fig. 9 Microstructure up to the surface of a 10 mm (½ in) casting; molten iron treated with moist-sand lance. Etched in 4% picral. ×50.

Fig. 10 Microstructure up to the surface of a casting of 22 mm (¾ in) section made in an uninoculated iron. Etched in 4% picral. ×50.

Fig. 11 Microstructure up to the surface of a casting of 22 mm (¾ in) section made with iron inoculated with 0-25% silicon (as foundry-grade ferrosilicon) in the ladle.
The most important effect of inoculation was to reduce the depth to which ferrite occurred. A similar effect was obtained whether ferrosilicon, calcium silicide, SMZ, or strontium-containing ferrosilicon were used as ladle and sprue inoculants.

Pouring temperature—Decreasing the pouring temperature of the iron from 1400°C to 1320°C had no effect on the quantity of ferrite or the surface hardness, as shown by the results in Table 14.

Casting-section size—the quantity of ferrite increased with increasing casting-section size and there was a corresponding striking decrease in surface hardness, as shown in Fig. 12. The results in this figure also show how the hardness near the centre of the casting decreased with increasing section size, and they confirm the marked influence of silicon.

Grade of shell-moulding sand—Test castings have been made under controlled casting conditions using eleven grades of shell-moulding sand. All the castings contained considerable quantities of ferrite, and in no instance was a fully pearlitic structure obtained. This suggests that ferrite is likely to occur in shell-moulded grey iron castings whatever grade of shell-moulding sand is used.

Shell-mould thickness—Increasing the thickness of the shell mould induced a greater rate of cooling in castings of 13 mm (½ in) section, particularly at temperatures between the eutectic and eutectoid arrests. This was probably responsible for the decrease in the quantity of ferrite as the shell-mould thickness was increased, and there was a corresponding increase in surface hardness—as shown in Fig. 13. This illustration shows that the increase in surface hardness was only significant in relatively small-section castings, and that the surface hardness of heavy-section castings may in fact decrease with increasing shell-mould thickness.

Fig. 12 Variation in surface hardness with section size, at three different silicon contents; uncovered mould.

Fig. 13 Effect of shell-mould thickness on surface hardness for castings differing in section size; uncovered moulds.

Fig. 14 Microstructure up to the surface of a 13 mm (½ in) casting made in a shell mould of 6 mm (0·25 in) thickness and bedded on moist sand—showing a graphite-free surface layer. Etched in 4% picrol. ×100.

Factors influencing the microstructure in the immediate surface zone

Although shell-moulded castings contain ferrite, in many instances the immediate surface zone is fully pearlitic to a depth of 0·1 mm (0·005 in) or so.
However, if a shell-mould is bedded on warm or moist sand, then the fully ferritic surface rim can occur, especially if the castings are of fairly heavy section. It has been suggested that surface decarburization at temperatures of around 1000 °C accounts for the formation of this ferritic rim.

When a very thin shell-mould was bedded on moist sand, the bottom surface of the casting had a pronounced graphite-free layer, as shown in Fig. 14. This layer is similar to that which often occurs on castings made in greensand moulds, and is known to be associated with surface decarburization caused by the presence of water vapour in the mould atmosphere. The graphite-free layer observed when a thin shell-mould is backed by moist sand is also probably caused by surface decarburization associated with the early breakdown of the shell mould and the ingress of water vapour to the casting surface.

Suppression of general ferrite

The greatest quantity of ferrite has been shown to occur when the shell-mould surface is exposed to the air; 50 per cent ferrite was present in the surface 1-3 mm (0.05 in) layer, and surface hardness values as low as HB 150 were obtained.

Backings of the mould or artificially cooling the casting—Backings the moulds with cast iron shot or moist sand suppressed ferrite, and surface hardnesses were increased to values above HB 200. The use of a drysand backing was not so effective, in reducing the quantity of ferrite, as moist sand or cast iron shot.

The fineness of the backing sand was found to have no effect on the quantity of ferrite or on surface hardness values, but raising the moisture content of the backing sand increased the surface hardness of the castings, as shown in Fig. 15. It has been shown in a previous paper that backing the shell mould was most effective when relatively thin moulds were used, or for relatively heavy-section castings.

Spraying the moulds with water after the casting had solidified, or knocking the castings out of the moulds while they were hot and allowing them to cool in still air, sometimes caused a marked increase in surface hardness—as shown by the results in Table 3.

The comparative effectiveness of the various mould-backing materials and of water-spraying the mould, in suppressing the ferrite, is shown in Fig. 16. In addition to reducing the quantity of ferrite, these methods also reduced the depth to which ferrite occurred.

![Fig. 16 Distribution of ferrite up to the surface of 13 mm (1 in) castings made in shell moulds with various backing materials.](image)

Table 3 Effect of water-spraying the mould & knocking castings out hot, on the surface hardness of shell-moulded castings.

<table>
<thead>
<tr>
<th>Casting</th>
<th>Casting cooled to room temperature in the mould</th>
<th>Mould sprayed with water after casting</th>
<th>Casting knocked out of mould 10 min after pouring &amp; air-cooled</th>
</tr>
</thead>
<tbody>
<tr>
<td>Section</td>
<td>Casting</td>
<td>Mould sprayed</td>
<td>Casting</td>
</tr>
<tr>
<td>size, mm (in)</td>
<td>cooled</td>
<td>with</td>
<td>after</td>
</tr>
<tr>
<td>10 (2)</td>
<td>195</td>
<td>181</td>
<td>214</td>
</tr>
<tr>
<td>22 (8)</td>
<td>138</td>
<td>207</td>
<td>205</td>
</tr>
<tr>
<td>25 (1)</td>
<td>146</td>
<td>232 Top</td>
<td>311 Base</td>
</tr>
</tbody>
</table>

Fig. 15 Effect of moisture content of the backing sand on surface hardness.

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The effect of the washes on the quantity of ferrite and surface hardness is shown in Table 4. The tin and arsenic washes had only a small effect in reducing the quantity of ferrite. The antimony wash was the most effective, and it promoted a pronounced pearlitic band near the cast surface as shown in Fig. 17. This figure should be compared with Fig. 18 which is for a similar casting made in a mould without a wash.

Metal additions—Table 5 shows that small laddle-additions of tin and arsenic had a similar effect in reducing the quantity of ferrite, and again antimony was the most effective. The microstructures up to the surfaces of the castings containing tin or antimony are illustrated in Figs. 19 & 20, and these should be compared with Fig. 18. Surface-hardness values above HB 200 were obtained whenever any of the metal additions were used (Table 5).

### Practical significance of results

It has been demonstrated that appreciable quantities of ferrite occur in grey iron castings when they are made in shell moulds. The casting procedure used in many foundries, where the shell moulds are simply placed on a sand bed, laid on pallets or supported by rails, has been shown to be the worst condition for promoting ferrite—and consequently low surface-hardness values are often obtained. Shell-moulded castings of 10-35 mm (3/8-1 3/8 in) section having fully pearlitic structures would be expected to have hardneses in the range HB 180-220, but in fact surface hardneses as low as HB 130-150 are common. There is a direct relationship between the quantity of ferrite near the surface, and the surface hardness; consequently, any factor which reduces the quantity of ferrite causes an increase in surface hardness, and vice versa.

The results suggest that the ferrite is unlikely to be significantly reduced merely by changing the grade of sand used for the shell moulds. In order to reduce the quantity of ferrite, and to prevent the occurrence of low surface-hardness values, an inoculated iron should be used with carbon and silicon contents as low as practicable consistent with obtaining freedom from chill. A silicon content of 2.0-2.2 per cent seems to be advisable in most instances. There should be a minimum of delay between the inoculation treatment and pouring the casting. Additionally, the manganese and sulphur contents of the iron should be accurately balanced according to the formula %Mn = 1.7/× %S, but the levels of manganese and sulphur required are critical, and, in practice, some difficulty might be experienced in achieving a consistent balance. Alternatively, the iron could have a relatively high excess-manganese content of about 1 per cent. The use of a high-nitrogen non-graphite carburizer would also tend to reduce the quantity of ferrite, but care would be required to ensure that nitrogen defects were avoided.

Castings of less than 13 mm (1/2 in) section should be made in moulds 10-13 mm (0.4-0.5 in) thick in order to obtain a more or less fully pearlitic structure up to the cast surface. Castings of 25 mm (1 in) or more in section should be made in the thinnest moulds possible in order to promote the rapid breakdown of the shell mould, and the moulds should be backed so that only a minimum
quantity of ferrite occurs, and excessive distortion is prevented. In practice, foundries should find the optimum thickness by trial, for each casting, bearing in mind the above suggestions.

Although backing the shell mould with a moist material causes a marked increase in surface hardmess, it may sometimes have disadvantages. A pronounced ferrite skin may be promoted in the immediate surface zone, and although this is usually quite shallow—less than 0.25 mm (0.01 in)—it could have a detrimental effect on the machined finish if there was only a small machining allowance over a relatively large surface area. More important, however, is that the use of a thin shell-mould sometimes results in the formation of a graphite-free surface layer which can have a detrimental effect on machinability. If this is a problem, cast iron or steel shot or some other dry backing material should be used, rather than a moist one. It should be emphasized, however, that graphit efree surface layers are not a regular feature of shell-moulded castings and none were observed during the survey of commercially produced castings.

Although spraying the moulds with water can be an effective way of reducing the quantity of ferrite, it can involve engineering difficulties. Some forms of spray cabinet might be used, but if more than a mist spray is employed, efficient water extraction can be a problem. Additionally, spraying the shell moulds with water after the casting has solidified, or knocking the castings out of the moulds at temperatures above the lower critical temperature, would only be suitable methods for reducing the quantity of ferrite for castings of fairly uniform section. This is because, to obtain the maximum effect, the time at which spraying is started or the castings are knocked out is critical for a given casting section-size. If the castings are knocked out of the moulds in the hot condition, they must be allowed to air-cool naturally and they should not be stacked. If the castings are knocked out too hot, surface decarburization is likely to occur and this can result in a marked ferrite skin.

Although the use of mould washes containing pearlite-promoting elements, such as tin, arsenic or antimony, sometimes reduces the quantity of ferrite, particularly near the cast surfaces, some deterioration in the surface finish of the casting can occur.

These results of the present work have shown that an addition of tin, arsenic or antimony to the metal is an effective way of reducing the quantity of ferrite in shell-moulded castings, and in most instances this would be a more convenient method than the use of a mould wash containing these elements. However, the level of addition of antimony and arsenic used were rather high, and it is suggested that in practice these elements should be maintained at levels below 0.05 per cent to avoid a possible reduction in the ductility of the iron. Tin is, therefore, probably the most suitable metal addition, even though it may not be so effective in reducing the quantity of ferrite.

Application of results in industry

The results of the present investigation have been successfully applied in two foundries making shell-moulded grey iron castings. In both instances, some difficulty had been experienced in meeting the specified hardness requirement. Substantial increases in surface hardness were achieved

Table 5 Effect of metal additions on the quantity of ferrite & surface hardness of castings of 13 mm (1/2 in) section, shell moulds supported by rails.

<table>
<thead>
<tr>
<th>Metal addition</th>
<th>% ferrite in surface 1/3 mm (0.030 in)</th>
<th>Depth to which ferrite occurs x mm (x 10^-1 in)</th>
<th>Surface hardness HB 6750</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td>45</td>
<td>0.033 (59)</td>
<td>178</td>
</tr>
<tr>
<td>0.01% Tin</td>
<td>20</td>
<td>0.016 (40)</td>
<td>209</td>
</tr>
<tr>
<td>0.01% Arsenic</td>
<td>16</td>
<td>0.016 (40)</td>
<td>202</td>
</tr>
<tr>
<td>0.01% Antimony</td>
<td>6</td>
<td>0.012 (30)</td>
<td>216</td>
</tr>
</tbody>
</table>

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by backing the shell moulds with sand or metal shot, and the results confirmed that—to have the greatest effect—both halves of the mould should be covered and the mould should be as thin as possible. These measures were as effective as the addition of 0.1 per cent of tin to the metal. Backing the shell moulds also reduced the variation in hardness within a spray of castings.

**Conclusions**

1. Excessive quantities of ferrite often occur in grey iron castings made in shell moulds, and this is concentrated near the cast surfaces. The ferrite occurred when the moulds were made of sands in any of the wide range tested.

2. The greatest quantities of ferrite occur in relatively heavy-section castings, especially when the shell-mould surface is exposed to the air—for example, if the mould is lightly batted on sand, laid on a pallet, or supported by rails—and when manganese is present in a small excess over that required to chemically balance the sulphur, for instance if $\% \text{Mn} = 1.7 \times \% \text{S} + 0.3\%$. These conditions are typical of those in many grey-iron foundries, so 50 per cent or more ferrite is likely to occur near the surfaces of their castings and surface hardnesses be lower than 115 HB 150.

3. The ferrite in shell-moulded grey iron castings affects their load-bearing capacity in service, and can be the cause of poor machined finish. The presence of ferrite also affects casting-quality assessment, particularly if this is based on surface hardness measurements.

4. The quantity of ferrite which occurs in shell-moulded grey iron castings can be reduced by the following measures:
   (a) using an iron with the lowest feasible carbon and silicon contents, provided that chilling is avoided;
   (b) Ensuring that the manganese and sulphur contents are accurately balanced according to the formula $\% \text{Mn} = 1.7 \times \% \text{S}$, or raising the excess-manganese content of the iron to about 1 per cent;
   (c) Ensuring that the iron is well inoculated and that there is a minimum of delay before pouring the castings;
   (d) Controlling the shell-mould thickness—a thick mould for thin castings, a thin mould supported by a backing material for relatively heavy-section castings;
   (e) backing the shell mould with cast iron shot, moist or dry sand, which if both surfaces of the mould are backed—can be as effective as the addition of 0.1 per cent tin to the iron;
   (f) using a mould wash containing tin, arsenic or antimony—and antimony is the most effective in reducing the quantity of ferrite, especially that near the cast surface;
   (g) adding tin to the iron;
   (h) spraying the moulds with water after the casting has solidified, or knocking the castings out of the moulds at temperatures above about 750 °C and allowing them to air-cool; however, these methods are only suitable for castings of fairly uniform thickness.

5. The presence of hydrogen in the melt, or the use of a high-nitrogen re-carburizer, is likely to reduce the quantity of ferrite in a shell-moulded grey iron casting, but if the gas content reaches too high a level, defects are likely to occur. Increasing the gas content of the metal is therefore not generally recommended as a suitable method of suppressing ferrite.

6. The ferrite occurring with fine graphite forms from austenite directly, as a shell-moulded grey iron casting cools through the eutectoid temperature. The ferrite surface rim, on the other hand, begins to form because of surface de-carburization at temperatures above the eutectoid.

7. A graphite-free surface layer can sometimes occur on grey iron castings made in shell moulds which are backed by a moist material, especially if the mould is very thin. This layer, which would be expected to cause machining difficulties, may be avoided by the use of dry backing materials.

**REFERENCES**


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