4.5 Solidification of \( LTF \) regions during final stage of solidification of VG iron

4.5.1 Characteristics of the liquid in the \( LTF \) regions

(1) Wider range

Figure 4-24 compares the size of the \( LTF \) regions of three types of cast iron under the same cooling condition. Since the tips of graphite in grey iron are in contact with the liquid, the two phases in the eutectic cells grow in a fully cooperative manner, resulting in less remaining liquid between the cells. The number of eutectic cells in SG iron is much more than in VG iron, thus the area of the \( LTF \) regions is also less. Compared with grey iron and SG iron, VG iron has the largest percentage of the \( LTF \) area in the field of view.

(a) Grey iron

(b) VG iron

(c) SG iron

![Comparison of LTF areas](image)

Fig. 4-24: Comparison of the \( LTF \) areas of three types of cast iron (sample section thickness 25 mm)

(2) With more segregation elements

In VG iron, except for the modification elements Mg, Ce and Ca, there also exist interference elements Ti and Al, which are easily enriched in the \( LTF \) regions.

4.5.2 Microstructure formed in the \( LTF \) regions

When the temperature of the liquid in the \( LTF \) regions drops to its crystallisation temperature, the liquid solidifies; depending on its composition, contamination by impurities and the cooling rate, the structures formed in the \( LTF \) regions are different.

(1) 'Basket' net-work structure of pearlite

The remaining liquid in the \( LTF \) regions is enriched in Ce, Ti and Mn, which increase undercooling of the liquid, thus promoting nucleation of austenite. Therefore, austenite dendrites often form in the \( LTF \) regions (see Fig. 4-25); these dendrites contact and integrate with the austenite grown from eutectic cells. Because VG iron contains more positive segregation elements than SG iron or grey iron, during solid phase transformation, the austenite in the \( LTF \) regions has a stronger tendency to form pearlite than in
grey iron or SG iron, and the spacing of pearlite is finer (see Fig. 4-26). When the pearlitic structures around eutectic cells connect with each other, a metallic net-work skeleton is formed, called a ‘basket net-work structure’ [34, 35], this is illustrated in Fig. 4-27. The ‘basket net-work structure’ consisting of pearlite (or ferrite) has a favourable effect on the mechanical properties of VG iron and enables VG iron to have an ideal combination of properties.

(2) Small graphite nodules
In the LTF regions, small graphite nodules are often observed (see Fig. 4-28). And in slow-cooled, thick section VG iron, small graphite nodules are even more in evidence. The formation of small nodules is related to a higher content of spheroidizing elements, Ce and Mg. From their location and size, it is known that small nodules are formed in the last stage of solidification; different from small nodules, the isolated and randomly distributed large nodules are formed in the early stage of solidification. The small nodules have a beneficial effect on the properties of VG iron.

(3) Flake graphite
In the LTF regions, when the spheroidizing elements are insufficient, anti-spheroidizing elements are excessive, or residual sulphur is too high, flake graphite is easily formed, as illustrated in Fig. 4-29. This flake graphite markedly weakens the strength of the metal matrix and is unfavourable to the mechanical properties of VG iron.

(4) Carbides
Since the completion temperature of eutectic solidification of VG iron, $T_{es}$, is higher than that of SG iron and is above the metastable eutectic temperature, the carbide forming tendency in the LTF regions of VG iron is weaker than that of SG iron.
Nevertheless, if the liquid in the LTF regions contains a too high level of positive segregation elements, their corresponding compounds can also form in the LTF regions; TiC is a commonly observed carbide in VG iron, as shown in Fig. 4-21c.

4.6 Solidification morphology of VG iron

4.6.1 Solidification process of VG iron

Using thermal analysis, liquid quenching and colour metallurgy to observe and analyse the formation, distribution and relationship of solidification structures, it is possible to effectively study the solidification process of VG iron. Figure 4-30 shows the thermal analysis curve of a VG iron with eutectic composition; the microstructure corresponding to the points on the curve are shown in Fig. 4-31. It can be seen from these figures that at the beginning of eutectic solidification (point ‘a’), the structure, similar to that of SG iron at this point, consists of small graphite nodules and divorced austenite dendrites. When reaching point ‘b’, the nodule ‘germs’ degenerate towards vermicular graphite, the eutectic graphite nodule count decreases gradually, a large number of eutectic cells begin to form, and recalescence appears on the cooling curve. On reaching point ‘c’, eutectic reaction nears the final stage, but eutectic cells continue to grow. Finally, the thermal curve reaches point ‘d’ and the liquid in the LTF regions solidifies; small nodules, vermicular graphite and austenite form, and solidification is complete.

![Fig. 4-30: Thermal analysis curve of a VG iron with eutectic composition](image)

(a) VG ‘germs’ and austenite dendrites precipitate  
(b) Eutectic cells form  
(c) Eutectic cells grow  
(d) LTF regions solidify

![Fig. 4-31: Formation process of solidification structures of VG iron (corresponding to the points on the curve shown in Fig. 4-30)](image)
4.6.2 Characteristics of solidification cooling curve of VG iron

VG iron is a type of intermediate cast iron between grey iron and SG iron; the characteristic freezing parameters are also in between grey iron and SG iron, as shown in Fig. 4-32(a). However, for a VG iron with hypoeutectic composition, the measured cooling curve shows other characteristics, as illustrated in Fig. 4-32(b).

The obvious difference is that the chilling tendency of the eutectic reaction of a hypoeutectic VG iron is higher than that of grey iron and SG iron as well. The reasons for this difference are: (1) hypoeutectic composition; (2) the vermicularizing elements Mg and Ce remarkably increase undercooling; (3) highly efficient inoculants cannot be used because they will increase nodule count and reduce the percentage of vermicular graphite.

4.6.3 Solidification morphology of VG iron

Although the morphology characteristics of VG eutectic cells are closer to those of grey iron, the solidification does not totally follow the mode of grey iron: i.e. gradually increasing the thickness of its solid layer (a successive layer-type solidification mode). The author considered that in comparison with grey iron, VG iron has 3–5 times wider LTF regions around the eutectic cells, a smoother outer contour of the eutectic cells and slightly more eutectic cells, all of which result in the variety of solidification processes.

At the edge of a VG iron casting, because of fast cooling, rapid solidification does not allow the LTF regions to develop and solidification occurs in a successive layer-type mode, whilst in the centre of the casting, solidification occurs mainly in a mushy mode. The influence of wall section thickness has a similar effect to the above; experimental measurements have shown that for castings of less than 10 mm thick, solidification is mainly the successive layer-type mode; for castings with a section thickness above 25 mm, the solidification occurs mainly in the mushy mode; see illustrations in Fig. 4-33. In addition, it was found that for castings with a section thickness up to 50 mm, the size of eutectic cells increases with increasing section thickness; for castings thicker than 50 mm, the size of eutectic cells does not show a significant increase with increasing section thickness. Figure 4-34 shows the solidification microstructure in sections with thicknesses of 10, 25 and 50 mm, respectively. The outer contour of eutectic cells in thin-walled VG iron is not very round, whilst in thicker sections above 25 mm, the eutectic cells show a clear and round outer contour.

The degree of vermicularization (percentage of vermicular graphite) has an important influence on the solidification morphology; see Fig. 4-35. For under-vermicularized VG iron in which vermicularization is insufficient, there exists more flake graphite and insufficient vermicular graphite; the solidification is similar to grey iron, solidifying in the successive layer-type mode. Conversely, for over-vermicularized VG iron, the nodularity is too high and in addition to the VG eutectic cells there exists some SG eutectic cells; under these conditions, the solidification occurs as a mixture of successive layer-type mode plus mushy mode, as shown in Fig. 4-35(c). The dendritic structure, vertical to mould wall, is shown in Fig. 4-36. The picture shows that at the edge of the casting the structure is austenite with graphite spheroids enveloped in it, whilst at the centre of the casting, the structure consists of VG eutectic cells.

4.7 Segregation in VG iron

The micro-segregation of VG iron is more complicated than in SG iron or grey iron. This is because VG iron contains more and complex solute elements than either SG iron or grey iron. The distribution of elements in various structures follows the common rules of segregation: negative segregation elements preferentially concentrate in the early-formed austenite, whilst positive segregation elements are enriched in the LTF regions; this causes the formation of pearlites, carbides or small graphite nodules around eutectic cells. The non-uniform distribution of various elements and structures in thick-section VG iron is more evident, as shown in Fig. 4-37. Table 4-3 lists the element content in corresponding regions; it can be seen from the table that the non-uniform distribution of positive and negative elements is quite severe. VG iron normally contains a higher Si content than grey iron and often reaches the level of as-cast ferritic SG iron. The segregation of such high Si in the centre of eutectic cells causes ferrite to form, but around the eutectic cells the structure is pearlite.
Fig. 4-33: Influence of section thickness on the macro-solidification structure of VG iron

References


Fig. 4-34: Influence of section thickness on the micro-solidification structure of VG iron
(Each group has two pictures of the same field of view, the left one is un-etched)

(a) Section thickness 10 mm

(b) Section thickness 25 mm

(c) Section thickness 50 mm


[19] Chisamera M, Riposan I and Barstow M. S-Inoculation of Mg-treated Cast Iron to Obtain CG Cast Iron and Improve Graphite
Table 4-3: Element distribution in the solidification structures of VG iron (mass %)

<table>
<thead>
<tr>
<th>Region in Fig. 4-37</th>
<th>Negative segregation element</th>
<th>Positive segregation element</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Si</td>
<td>Ni</td>
</tr>
<tr>
<td>A (in the austenite around primary nodules)</td>
<td>2.75</td>
<td>0.062</td>
</tr>
<tr>
<td>B (in VG eutectic cells)</td>
<td>2.68</td>
<td>0.058</td>
</tr>
<tr>
<td>C (in chunky graphite eutectic cells)</td>
<td>2.56</td>
<td>0.053</td>
</tr>
<tr>
<td>D (in the LTF regions)</td>
<td>1.90</td>
<td>0.027</td>
</tr>
</tbody>
</table>

(a) Hot alkaline etched
(b) Nital etched [the same field of view with (a)]

Fig. 4-37: The non-uniform phenomena of composition and microstructure distribution in a VG iron