Investigation of cooling rate dependent dendrite morphology in hypoeutectic lamellar cast iron

PÉTER SVIDRÓ, LENNART ELMQUIST, IZUDIN DUGIC, ATILÁ DIÓSZEGI
Investigation of cooling rate dependent dendrite morphology in hypoeutectic lamellar cast iron

Péter Svidró¹a, Lennart Elmquist¹b, Izudin Dugic², Attila Diószegi¹c

¹ Department of Mechanical Engineering/Materials and Manufacturing, School of Engineering, Jönköping University, P.O. Box 1026, 551 11 Jönköping, Sweden
² Department of Mechanical Engineering, Faculty of Technology, Linnaeus University, 351 95 Växjö, Sweden
E-mail: peter.svidro@jth.hj.se¹a, lennart.elmquist@jth.hj.se¹b, izudin.dugic@lnu.se², attila.dioszegi@jth.hj.se¹c

Abstract

Shrinkage porosity and metal expansion penetration are two fundamental defects appearing at production of complex shaped lamellar cast iron components. In previous work it has been shown that both shrinkage porosity and metal expansion penetration are related to the primary austenite dendrite network and its formation mechanisms. The purpose of the present work is to study the morphology of primary austenite in test casting with a high tendency to form shrinkage porosity and metal expansion penetration. Simplified test models simulating the thermal and geometrical conditions similar to the conditions existing in complex shaped casting have been successfully used to provoke shrinkage porosity and metal expansion penetration.

Stereological investigation of the primary dendrite morphology indicates a maximum interdendritic space in connection to the casting surface where the porosity and the penetration defect appear. Away from the defect formation area the interdendritic space decreases. Furthermore the local solidification times of the investigated samples were calculated in a 3D simulation software. Comparison of the simulated local solidification times and measured interdendritic space indicates a strong relation of the same shape as it is known from the literature when dynamic coarsening mechanism is characterized. The main outcome of the present paper is the observed gradient of increasing interdendritic space from sections with high local solidification to sections with low solidification time. The mechanism of increasing the interdendritic phase can be explained by the dynamic ripening process. The unfortunate thermal conditions with the slowest local solidification time situated in the border between the casting surface and its surrounding are considered the reason to form an austenite morphology which can promote the mass flow between dendrite provoking shrinkage porosity or metal expansion penetration.

keywords: lamellar cast iron; primary austenite; dendrite morphology; coarsening;

1. Introduction

Lamellar cast iron is an important, widely used engineering material because of the mechanical properties. These properties of the as-cast part are defined by the microstructure developed during solidification. Solidification of lamellar cast iron is a complex procedure and involves the possibility of defect formation. Two recurring defects are the shrinkage porosity and the metal expansion penetration. Complex castings like cylinder heads or blocks are more exposed to form these defects. According to the literature, relations of these type of defects to volumetric changes during solidification and their formation around the dendrite coherency is generally agreed. From the dendrite coherency, property of the primary dendrite network affects the feeding features of the residual liquid. This is important as shrinkage porosity is a material deficit, metal expansion penetration is a material excess defect. Primary dendrites develop with volumetric extension between the nucleation and the dendrite coherency. At the dendrite coherency primary crystals impinge on each other and the volumetric growth is blocked, further growth of the phase driven by the coarsening of the dendrite arms [1]. Coarsening - also known as Ostwald ripening – is a surface energy driven morphological change by the intention of the combination of liquid-solid to minimize the free energy of the two phase system originated from the thermodynamic imbalance of the phases [2]. In terms, this is a reduction of the interfacial area of the primary dendrites over time [3]. Primary dendrite coarsening consequently is the increase of the interdendritic space [4]. As coarsening occurs over time, interdendritic space extends with the solidification time.
The temperature distribution in complex shaped castings is variable due to the variation of the heat extraction to the surroundings, provoking the migration of the hot spots. [5]. Areas with longer solidification time positioned near to the mold / casting surface may promote the formation of either shrinkage or penetration defect. The aim of the present work was the quantitative analysis of the primary austenite morphology in the defected areas along with the defect free areas within a casting and to compare it with simulated solidification times. Investigations have been made on shrinkage porosity and metal expansion penetration defected as-cast samples. The results show strong relation between the interdendritic space and the local solidification time.

2. Experimental procedure

The scope of the measurement was the quantitative analysis of the primary austenite morphology in regions affected by shrinkage porosity and metal expansion penetration. Samples taken from castings previously developed to represent the thermal conditions like in a complex shaped casting, hence promote the formation of designated casting defects. Material of the casting alloys was hypoeutectic gray cast iron similar to alloys used in ordinary production of automotive cast components.

2.1. Shrinkage porosity

Casting called cylinder head simulator (CHS) have been developed to simulate the thermal conditions like in a cylinder head casting (Figure 1), and provoke shrinkage porosity [6]. This is obtained with a 15 [mm] thick plate positioned next to three cylinders with a diameter of 40 [mm] and the height of 100 [mm] straddled by two parallel plates lower of 20 [mm], top 10 [mm] in thickness. The distance between the cylinders and the vertical plate is 7 mm. The specimens were cast into an Epoxi-SO2 hardened sand mold. For chemical compositions see Table 1.

<table>
<thead>
<tr>
<th>Melt no.</th>
<th>C[%]</th>
<th>Si[%]</th>
<th>Mn[%]</th>
<th>P[%]</th>
<th>S[%]</th>
<th>Cr[%]</th>
<th>Mo[%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>3.283</td>
<td>1.958</td>
<td>0.643</td>
<td>0.030</td>
<td>0.056</td>
<td>0.261</td>
<td>0.045</td>
</tr>
</tbody>
</table>

Table 1. Chemical composition of shrinkage porosity sample

Casting has been cut into the half at the middle cylinder as it is indicated on Figure 1, investigations have been made on the lower half area as indicated on Figure 2 and Figure 3, where the defects (Figure 4) were found.
2.2. Metal expansion penetration

Casting called metal expansion penetration simulator (MEP) have been developed to provoke penetration defect (Figure 5 and Figure 7). This is obtained with a concave casting surface of a diameter 30 [mm] thick stem positioned in the middle of a diameter 80 [mm] cylinder simulating a core similar to that used in cylinder head production [7]. Specimens were cast from the top into an organic binder-SO₂ hardened sand mold shown in Figure 5. After filling, the sample was covered by a sand lock to create an even heat extraction in all directions out from the sample. For chemical compositions see Table 2.

<table>
<thead>
<tr>
<th>no.</th>
<th>C[%]</th>
<th>Si[%]</th>
<th>Mn[%]</th>
<th>P[%]</th>
<th>S[%]</th>
<th>Cr[%]</th>
<th>Mo[%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.18</td>
<td>1.77</td>
<td>0.56</td>
<td>0.045</td>
<td>0.09</td>
<td>0.15</td>
<td>0.24</td>
</tr>
</tbody>
</table>

Table 2 chemical composition of metal expansion penetration sample

The casting has been cut into the half and was investigated on the surface as indicated on Figure 6. The MEP is rotational-symmetric and penetration defects appeared evenly distributed, so only the half of the surface have been selected.

2.3. Image analysis and stereological definitions

After sample preparation color-etching were performed on the surfaces to reveal primary austenite [8]. Pictures for investigation have been taken from the defected areas and the surroundings. At 2,5x magnification, one frame represents an approximate 5 [mm²] area.

Color-etching is a very useful technique to reveal the microstructure, but automated systems like commercial image analysis software cannot distinguish the phases appearing within the same color range. Both primary austenite and eutectic colonies appear with blue tone (Figure 9), color distribution is dependent on the Si segregation between the primary austenite and the eutectic austenite. In absence of proper software solution, phases have to be separated before quantitative analysis.
For this purpose an interactive pen display was used, phases were marked by hand drawing (Figure 10). Due to the Si segregation in both the primary austenite and the secondary austenite forming the eutectic cells in collaboration with graphite, it is difficult to distinguish the exact morphology of the primary austenite. Those areas not distinguishing clearly the contour of the primary phase are excluded from the investigation. Those areas are represented by black color in Figure 10. The well distinguishable primary austenite surfaces are colored white in Figure 10. The remaining gray area in Figure 10 represents the interdendritic space. Quantitative analysis has been done with an open source image analysis software on the preprocessed images.

Quantitative analysis has been done with an open source image analysis software on the preprocessed images.

Two morphological parameters with respect to the primary dendrite were investigated. Secondary dendrite arm spacing (SDAS) given in \( \mu m \) was measured as well the surface area \( A_i \) of the interdendritic phase and the perimeter \( P_i \) between the observed primary austenite phase and the interdendritic space. Recent research work [4] discussed the fraction between the surface area of interdendritic space and its perimeter and showed corresponding to the hydraulic diameter of the interdendritic space \( D_h = \frac{A_i}{P_i} \) with a unit of \( \mu m \).

The Hydraulic diameter / interdendritic space has been shown to vary with respect to the local solidification time as SDAS do and can be interpreted as a mechanism of dynamic ripening.

The local solidification times have been calculated for comparison to the measured morphological parameters by a commercial simulation software MAGMASoft® considering the casting temperature and chemical composition.

3. Results and discussion

Morphology of the primary austenite is connected with solidification time. Time of solidification is generally dependent on the rate of heat extracted from the melt by the mold toward the environment. The heat transport on the mold/melt interface can be expressed by a thermal gradient. This gradient defined by the temperature difference between the mold and melt and inversely proportional to the solidification time. In the case of high temperature difference, the thermal gradient is big therefore the solidification time is short. Accordingly, when the temperature difference is low, the thermal gradient is small and the solidification time is long. Increased solidification time facilitate the coarsening of the primary dendrites causing extended interdendritic space.

Quantitative analysis of the indicated areas shows variances in the interdendritic spaces. Differences are clearly shown on the CHS sample, comparing the average of \( D_h = 23 \ \mu m \) of the right side of the investigated area representing the surface of the middle cylinder closer to the vertical plate with the average of \( D_h = 18 \ \mu m \) of the left side representing the outer surface of the cylinder (Figure 11). This can be explained with a reduced thermal gradient near to the mold/metal surface. Looking at the mold volume, on the outer side of the cylinder is bigger, and the mold able to transfer the heat from the melt toward to the environment. Compared to this, heat transfer properties of the mold area situated between the cylinder and the vertical plate is reduced. It becomes thermally overloaded in a certain time result in the reduction of thermal gradient therefore the longer solidification time. The same effect is shown on the MEP sample (Figure 12). Heat can leave the melt to the surrounding mold almost evenly. However core trapped in the thermal center of the casting not able to transfer the heat in the same rate like the other parts of the mold.
Subsequently, the thermally overloaded core causes the same effect mentioned above. Results have been conditional formatted to visualize the differences. Light tone represents the lower, dark tones of the high values.

Figure 11. Hydraulic diameter measured at different positions of a CHS solidification sample

Figure 12. Solidification time simulated at different positions of a CHS solidification sample

Image analysis on defected areas indicate the highest interdendritic spaces, what can be understand as areas with the longest solidification times. Simulated solidification times corresponds with the interdendritic space measurements, as defected areas have the longest solidification times in the case of CHS (Figure 13) and MEP (Figure 14). Considering the solidification simulations, these areas are also the last to solidify parts of the casting, near to the mold/metal interface. Increased interdendritic space promotes the movement of the remaining liquid in the very end of the solidification, therefore promotes the formation of both shrinkage porosity and metal expansion penetration.

Figure 13. Hydraulic diameter measured at different positions of a MEP solidification sample

Figure 14. Solidification time simulated at different positions of a MEP solidification sample
Results from SDAS and $M_i$ measurements are plotted as a function of the calculated local solidification time in Figure 15 for results related to the CHS experimental unit and Figure 16 for results related to the MEP experimental unit. Furthermore, results from literature data [4] showing similar relations but observed on samples obtained during interrupted solidification were also introduced in the diagrams. Comparing with the literature data it seems that the variation of the morphology parameters ($M_i$ and SDAS) as a function of time obtained in the complex shaped test samples follows the similar trend as the results obtained on a simple shaped sample produced by interrupted solidification. The consequence of these similarities is that the governing mechanism for increasing the interdendritic space can be described by the dynamic ripening process. Deviation from the fitted lines on the literature data can be explained by the different nature of the experiments. The cited work was based on an artificial, simple geometry sample developed for solidification measurements, combined with temperature registration. This work based on complex geometry was developed for the promotion of casting defects and the solidification times have been calculated with simulation software. Nevertheless the slight differences in the results it is shown, that characterization of the dendrite morphology in connection with the solidification properties is more adequate to prepare with the hydraulic diameter of either the primary austenite or the interdendritic space rather than the SDAS measurement. Although the dendrite arm spacing measurement is a quicker solution, result coincidences with the real conditions stochastic, with a large standard deviation.

![Figure 15 Comparison of CHS sample results with literature data](image1)

![Figure 16 Comparison of MEP sample results with literature data](image2)

4. Conclusion
Shrinkage porosity and metal expansion penetration defected as-cast samples have been investigated by quantitative image analysis. The measurement shows that thermal properties of the mold-casting system have an effect on solidification time. Divergent local solidification times influence the austenite morphology. When the local solidification time increase, also the interdendritic space increases. The mechanism of increasing the interdendritic phase can be explained by the dynamic ripening process. The unfortunate thermal conditions with the slowest local solidification time situated in the border between the casting surface and its surrounding are considered the reason to form an austenite morphology which can promote the mass flow between dendrite provoking shrinkage porosity or metal expansion penetration.

Acknowledgment
The experimental part of the present work has been carried out within the JÄRNKOLL project, the analyzing part of the work has been performed within the JÄRNKOLL 2C project both financed by the Swedish Knowledge and Competence Foundation in collaboration between School of Engineering at Jönköping University, Volvo Powertrain AB and Scania CV AB. All contributors are acknowledged.
References


