Determination of the Columnar to Equiaxed Transition in Hypoeutectic Lamellar Cast Iron

Péter SVIDRÓ* and Attila DIÓSZEGI

Department of Mechanical Engineering/Materials and Manufacturing, School of Engineering, Jönköping University, P.O. Box 1026, 551 11 Jönköping, Sweden.

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Shrinkage porosity as a volume change related casting defect in lamellar cast iron was reported in the literature to form during solidification in connection to the dendrite coherency. The present work includes an experimental study on dendrite coherency – also called columnar-to-equiaxed transition in lamellar cast iron using thermal analysis and expansion force measurements. Investigation was carried out in order to study the mechanism of dendrite coherency formation. Cylindrical test bars were cast from the same alloy with different pouring temperature, amount of inoculant and time between the addition of inoculant and start of pouring the samples. Cooling rate and expansion force was recorded as a function of time. A numerical algorithm based on temperature differences measured under solidification was used to interpret the solidification process. Three different methods have been compared to determine the columnar to equiaxed transition. The compared methods were based on registered temperature differences, based on registered expansion forces during the volume change of the solidifying samples and based on the calculated released latent heat of crystallization. The obtained results indicate a considerable influence on the formation and progress of coherency due to variation of casting parameters. It has been shown that the coherency is not a single event at a defined time moment rather a process progressing during a time interval.

KEY WORDS: columnar to equiaxed transition; dendrite coherency; lamellar cast iron; inoculation.

1. Introduction

Shrinkage porosity is a recurring quality issue in the casting practice. Foundries producing parts for the marine or automotive industry with pressure tight demands like cylinder heads, blocks, spend lot efforts to prevent this type of casting defects. Porosity if connected like a network through a wall of a casting leads to leakage so the rejection of the part, resulting scrap increase with all of its negative impact on the production and the environment. According to the literature this type of casting defect is proposed to be formed in connection to the dendrite coherency. However a lot research work have been done on columnar to equiaxed transition, the exact mechanism of shrinkage porosity formation is still unclear.

Volumetric deficiency, inner contraction cavities inside grey iron castings are related to volumetric changes during solidification. Overall extent of this change is generally driven by the density changes and the solidification kinetics of the austenite and graphite phases, and also by the initiation and development of the primary solidification structure also called macrostructure. This macrostructure consists of columnar and equiaxed grains forming individual zones. After mold filling solidification begins as heat is transferred into the mold, dendrites starts growing from the wall into the melt all-around the mold wall creating a container shaped columnar zone respectively. Inside the melt, nucleation of the equiaxed grains starts on heterogeneous nucleation sites. The moment when the equiaxed and columnar grains fill up the volume is called dendrite coherency or the columnar to equiaxed transition (CET). According to the literature, shrinkage porosity in lamellar cast iron is most likely to form in connection to the dendrite coherency. Although the dendrite coherency is an important moment of the solidification, there are limited known investigation methods to perform the CET measurement and consequently there is no information on how metallurgical parameters are influencing when and at which fraction solidified primary phase the CET occurs. Most of the reported researches are focused on light alloys. Based on recently reported methods involving expansion force measurement and thermal analysis, CET in lamellar cast iron will be investigated.

The scope of this paper is to compare different identification methods when the CET is reached and also investigate how metallurgical parameters like the addition of inoculant or casting temperature influence CET.

2. Experimental Procedure

Cylindrical samples of Φ50 and length 350 [mm] were cast from the same alloy into a shell sand mold. Dimensions

* Corresponding author: E-mail: svidropeter@gmail.com
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of the drag and cope were 45 × 100 × 407 [mm]. Two thermocouples of type “S” (Pt-PtRh10) were placed perpendicular to the longitudinal axis of the cylindrical casting. Two measuring spots by thermocouples were placed, one in the thermal centrum equivalent with the cylinder’s rotational axis (TC), and one displaced 10 mm away from the axis to the cylindrical surface (TS). The temperature sensors were protected by a quartz tube (Φ5 external and Φ3 internal diameter [mm]) welded at the end to a hemisphere. Two quartz rods (Φ10 mm) were built in the mold’s parting line coinciding with the axis of the cylinder, aimed to transmit the expansion forces of the test bar. The mold with the quartz rods and the displacement sensors were assembled by a special frame on a table. The experimental assembly is shown in Fig. 1.

Lamellar cast iron melts were prepared in a 60-kg medium frequency induction furnace using returns of a commercial casting component. For chemical compositions see Table 1.

Melt has been poured into a ladle for preparation while Sr based commercial inoculant have been added into the stream. The amount of inoculant, the pouring temperature and the time interval between inoculation and pouring have been changed in individual charges. Overall 11 charges have been cast. For the combination of metallurgical parameters see Fig. 2 and Table 2.

In the case of the highest pouring temperature T3=1 440°C and shortest inoculation time t1=0 minute, the melt was cast immediately. In the other cases, melt was poured back into the furnace to maintain designated pouring temperatures and inoculation times. The signals from temperature and expansion force measurement were registered by a HBM-Beam U10 software system.

**Calculation of Fraction Solid by Thermal Analysis**

Cast alloys often have more than one solid phase precipitating from the liquid phase, where the transformation releases the latent heat of solidification. This released heat is assumed to be proportional to the fraction of solidified metal. Based on temperature measurement during solidification different types of numeric algorithms are known to calculate release of latent heat during solidification. In the present investigation when the goal of the measurement was to simulate release of latent heat during solidification. In the present investigation when the goal of the measurement was to simulate release of latent heat during solidification.

The inverse thermal analysis by means of Fourier method is derived from the general formula of Fourier’s heat transfer equation expanded with a heat source \( q \) corresponding to the released heat during solidification:

\[
\rho C_p \frac{\partial T}{\partial t} = \nabla (k \nabla T) + \dot{q} \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots (1)
\]

Considering \( k = \text{constant} \), \( \alpha = \frac{k}{\rho C_p} \), and \( \rho C_p = C_v \) then Eq. (1) can be rearranged as:

\[
\frac{\partial T}{\partial t} = \alpha \nabla^2 T + \frac{\dot{q}}{C_v} \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots (2)
\]

Further rearrangement of Eq. (2) and substituting \( \dot{q} \) by \( q_s \) and \( \frac{\partial T}{\partial t} \) by \( \dot{T} \), the released heat rate in the solidification interval can be calculated as function of time \( t \):

\[
q_s = C_v \dot{T} - C_v \alpha \nabla^2 T \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots (3)
\]

or

\[
q_s(t) = C_v(t) (\dot{T}(t) - Z_f(t)) \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots (4)
\]

**Table 1. Chemical composition.**

<table>
<thead>
<tr>
<th></th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Cr</th>
<th>Mo</th>
<th>Cu</th>
<th>Sn</th>
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<tbody>
<tr>
<td>min</td>
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<td>1.65</td>
<td>0.54</td>
<td>0.05</td>
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<td>0.15</td>
<td>0.21</td>
<td>0.77</td>
<td>0.05</td>
</tr>
<tr>
<td>max</td>
<td>3.78</td>
<td>1.82</td>
<td>0.64</td>
<td>0.05</td>
<td>0.11</td>
<td>0.17</td>
<td>0.25</td>
<td>0.92</td>
<td>0.08</td>
</tr>
</tbody>
</table>

**Table 2. Metallurgical parameters.**

<table>
<thead>
<tr>
<th>Casting temperatures [°C]</th>
<th>Inoculation time [min]</th>
<th>Inoculation content [w%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1=1320</td>
<td>t1=0</td>
<td>c1=0.05</td>
</tr>
<tr>
<td>T2=1380</td>
<td>t2=5</td>
<td>c2=0.10</td>
</tr>
<tr>
<td>T3=1440</td>
<td>t3=10</td>
<td>c3=0.15</td>
</tr>
</tbody>
</table>
where

\[ Z_f(t) = \alpha(t)\nabla^2 T \] .................................. (5)

Integrating the released heat for the time interval of solidification the latent heat of solidification can be calculated:

\[ L = \int_{t_a}^{t_b} q_s(t) \, dt \] .................................. (6)

Considering the solidification interval the released heat can be used to express the evolution of fraction solidified, by a cumulative function:

\[ f_s(t) = \frac{1}{L} \int_{t_a}^{t} q_s(t) \, dt \] .................................. (7)

The FTA method needs a tabulation of the volumetric heat capacity \( C_v \) of the phases taking part in the solidification. Several work found in the literature have been devoted to prove the accuracy of Fourier Thermal Analysis method.\(^{18,19}\)

Results calculated from measurements from experiment in position 14 are presented in Figs. 3 and 4. The released latent heat of solidification is proportional to the area between the cooling rate of the central thermocouple (\( \frac{dT_c}{dt} \)) collected from the experimental measurement and the calculated Fourier Zero line (\( Z_f(t) \)) curves as it is mentioned in Eq. (4), and shown in the upper part of Fig. 3. The calculated released heat \( q_s(t) \) and the corresponding fraction solidified \( f_s(t) \) are presented in Fig. 4.

3. Determination of the Columnar to Equiaxed Transition

Based on the literature a few methods exist to determinate the columnar to equiaxed transition mainly used for light alloys. One is a shearing force measurement. A rotating flat blade as a rotor inserted into the cooling melt and torque measured with DC motor\(^{20}\) or a viscometer.\(^^{21}\) Certain force is needed for the stirring of the pure liquid. During solidification primary crystals as columnar and equiaxed are developing and more force needed for stirring due to the increased viscosity. When the crystals create a rigid dendrite network, the stirring force increases remarkably, since it has to break the welded crystals. This breaking force is proportional to the contact surface of the rotor and the solid fraction of the melt. The drawback of this method on one hand is that stirring has an effect on the viscosity of the melt, on the other hand broken dendrite tips may act like nucleating sites turning over the initial columnar and equiaxed crystal balance.

Other method is the thermal analysis. Solidification kinetics is dependent on the thermal behavior of the solidifying material, this way temperature carry precious information. Simple thermal analysis like registering cooling curve with one thermocouple is a fast and easy technique to follow solidification. Coupled with critical parameters it is also a reliable practice in foundry process controlling. Enhanced the measurement with one more thermocouple, solidification characteristics can be investigated in deeper details. Through the calculations based on the results from two-thermocouples, CET can be determined by temperature differences and by the released latent heat.

These are discussed in details below together with the expansion force measurement as a novelty tool introduced in this paper for CET determination.

3.1. CET Determination by Temperature Differences (\(\Delta T\))

Determination of the columnar to equiaxed transition by temperature differences is based on the fact, that the thermal conductivity between the central part and the outer shell of the casting increases at the dendrite coherency. Conversely

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![Fig. 3](image-url) Measured cooling curves in the solidification interval and the cooling rate of the central thermocouple together with the calculated Fourier Zero line forms the field proportional to the Latent heat release.

![Fig. 4](image-url) Fraction of solid (\( F_s \)) and the rate of released heat (\( q_s \)) during solidification as a function of time.
this method uses two thermocouples, one in the center \( T_c \) and one displaced from the centrum toward the mold \( T_s \). Solidification of the cylindrical sample in the mold starts as heat transferred from the melt into the mold. Columnar crystals growing from the mold wall create a container like columnar zone compassing the remaining melt. Temperature in this container is lower than at the center \( T_c \). In the columnar zone temperature decreasing as the heat flows into the direction of the mold, at the same time released latent heat increases the temperature of the melt. Solidification continues with the nucleation and growth of equiaxed crystals. Developing primary crystals fill up the remaining space while more latent heat released rises the temperature. At the last moment before the crystals impinge the temperature difference \( \Delta T = T_i - T_r \) reaches its maximum. In a certain point advancing crystals touching each other, this is called dendrite coherency. As soon as the primary crystals created a coherent dendrite network in the remaining melt, the heat conductivity of the system suddenly increases as heat can be taken away through this network so \( \Delta T \) will decrease. Therefore dendrite coherency can be determined at the maximum of \( \Delta T \) (Figs. 6, 7 and Table 4). The present description to determine the coherency point by temperature differences was supported in the literature, investigating aluminum alloys.\(^{20,21}\)

### 3.2. CET Determination by Expansion Forces (F)

In previous work the authors introduced the concept for determination the dendrite coherency based on registered expansion forces.\(^{14}\) In the early stage of the solidification the columnar grains grow in competition with each other and perpendicularly to the mold surface. The stiffness of the columnar network is expected to be very low easily adapting the shape of the mold. The same time equiaxed grains are nucleated (Fig. 5(a)) in the liquid metal. Along with the progress of the columnar zone, the equiaxed crystals continue growing (Fig. 5(b)). When the crystals create a coherent network by touching each other it is called dendrite coherency (Fig. 5(c)). This moment can be determined with thermal analysis described in previous section. However an inner coherent dendrite network exists, this can be weak, cannot support the inserted quartz rods and able to break (Fig. 7). As soon as volume filled up with primary austenite crystals densely and zones welding into one system than it can be considered as one volume. The movement of the casting surface now represents the volume changes as a
whole (Fig. 5(d)).

Therefore the start of the continuous increase of expansion force corresponds to the presence of the coherent crystal frame rigid enough to support the quartz rods to transduce the force on the measuring unit. Consequently start of the continuous increase of expansion force $F$ indicate the columnar to equiaxed transition (CET).

### 3.3. CET Determination by the Rate of Released Latent Heat of the Crystallization ($q_s$)

As the amount of released latent heat is proportional to fraction of the solid phase the released latent heat increases in accordance with the nucleation and growth of the solid fraction. From a morphological point of view the equiaxed austenite grains start to develop as a small sphere until the austenite crystal acquires due to the advancement of the dendrite arms. The dominant morphological volumetric increase of the austenite crystal acquires due to the development of the primary and the lower order dendrite arms. The resulting increase of the density is supposed to promote a sedimentation of the growing grains. Results from CET investigation of two samples (14 and 19) where the differences in the casting process were based on the amount of added inoculant, are presented in Figs. 6, 7 and Table 4. Comparing the used CET determination methods (Table 3) in both cases the earliest CET as a function of the calculated precipitated solid fraction is identified when the rate of released solidification heat reaches the maximum ($f_{s}^{14} = 12.97$, $f_{s}^{19} = 7.89$).

This moment is interpreted as the moment when the first equiaxed grains impinge each other but the whole interspace enclosed by the columnar network (also associated with a container) is not completely filled by the equiaxed grains. CET determined based on the expansion measurement and the maximum temperature gradient, is indicated to occur at the same fraction solidified phase ($f_{s}^{14} = f_{s}^{19} = 20.29$). This indication of the CET is interpreted as the moment when the whole primary austenite network impinges and furthermore the stiffness of the grains is capable to withstand compressive tensile loads. An early coherency when a relatively low fraction solid phase is precipitated as it is indicated on Fig. 7, the developed coherency when a relatively low fraction solid phase is precipitated as it is indicated on Fig. 7, the developed coherency when a relatively low fraction solid phase is precipitated as it is indicated on Fig. 7, the developed coherency when a relatively low fraction solid phase is precipitated as it is indicated on Fig. 7.

### 4. Results and Discussion

The obtained results from the reported experiment are discussed with respect to the investigation methods presented in section 3 supported with the fraction solid calculations from the collected temperature data presented in section 2, in the study of columnar to equiaxed transition determination. Due to possible measurement failures sample 13, 18 and 22 are not displayed within the results.

#### 4.1. CET Interpreted as a Function of Precipitated Fraction Solid Determined by Different Methods

The fraction of solid phase inside a solidifying casting has an effect on the feeding properties - the movement of the remaining liquid. As the dendrite grains develop the liquid behind the grains is enriched in the negative segregated elements including carbon associated with increase of the liquid density. As the density of the growing dendrite grains increase even more then the liquid density, the difference in the density is supposed to promote a sedimentation of the growing grains. Results from CET investigation of two samples (14 and 19) where the differences in the casting process were based on the amount of added inoculant, are presented in Figs. 6, 7 and Table 4. Comparing the used CET determination methods (Table 3) in both cases the earliest CET as a function of the calculated precipitated solid fraction is identified when the rate of released solidification heat reaches the maximum ($f_{s}^{14} = 12.97$, $f_{s}^{19} = 7.89$).

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<table>
<thead>
<tr>
<th>Charge Nr.</th>
<th>$T_{	ext{casting}}$ [°C]</th>
<th>$t_{	ext{inoculation}}$ [min]</th>
<th>$m_{	ext{inoculation}}$ [w%]</th>
<th>$f_s$ at CET by $\Delta T$</th>
<th>$f_s$ at CET by $F_{\text{expansion}}$</th>
<th>$f_s$ at CET by $q_s$</th>
</tr>
</thead>
<tbody>
<tr>
<td>14</td>
<td>1440</td>
<td>0</td>
<td>0.05</td>
<td>20.3</td>
<td>20.3</td>
<td>13.0</td>
</tr>
<tr>
<td>15</td>
<td>1380</td>
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<td>0.10</td>
<td>16.7</td>
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<td>7.3</td>
</tr>
<tr>
<td>16</td>
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</tr>
<tr>
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</tr>
<tr>
<td>20</td>
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<tr>
<td>34</td>
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<td>5</td>
<td>0.10</td>
<td>15.7</td>
<td>26.7</td>
<td>8.1</td>
</tr>
</tbody>
</table>

#### Table 3. Fraction solid at CET determined by different methods.

<table>
<thead>
<tr>
<th>$f_s$ determined by</th>
<th>Sample 14</th>
<th>Sample 19</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_{s}^{14}$</td>
<td>12.97</td>
<td>7.89</td>
</tr>
<tr>
<td>$f_{s}^{19}$</td>
<td>20.29</td>
<td>13.82</td>
</tr>
<tr>
<td>$f_{s}^{14}$</td>
<td>20.29</td>
<td>13.82</td>
</tr>
</tbody>
</table>
Due to all compared results have a common dependence on the temperature measurement it can be concluded that the differences in the determined fraction primary austenite at CET within the same cast alloy indicate that the columnar to equiaxed transition is not a single moment rather an interval when the number of connecting points are increasing.

4.2. Influence of Inoculation on the CET

Experimental results based on the calculated fraction precipitated solid phase are collected in Table 4. An obvious observation is the influence of amount inoculant added to the melt independent neither on the parameters such as the casting temperature nor the time for inoculation nor the determination method on the CET. Addition of inoculant decreases the calculated fraction primary phase when the CET is reached under mostly of all condition and for all the determination cases. Considering the growth mechanisms of the primary austenite grains, differences in reaching CET under similar thermal conditions are possible only if the number of nucleated grains are different.

5. Conclusion

Methods used for CET determination combining thermal analysis and expansion force measurements show differences both in the time necessary to reach CET and the precipitated solid fraction when CET is reached. The maximum temperature difference indicates the first touch of the primary crystals. It is useful to assign the initiation of the interconnected dendrite network. Expansion force measurements detect the point when columnar and equiaxed crystals welding together forms a coherent system. Determining the CET by the maximum rate of released heat highlights the solidification differences related to the solid fraction.

The different volume fraction observed at CET using different determination methods, indicated the character of dendrite coherency being a transition over a period.

Acknowledgment

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