Relation between microstructure features, cooling curves and mechanical properties in CGI-cylinder block

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Abstract
The purpose of this master thesis was to evaluate variations in solidification and cooling rate in compacted graphite iron prototype cylinder blocks and for each position relate this to the microstructure and also relate the microstructure to mechanical properties. This has been done to increase the knowledge to predict mechanical properties in cast iron components.

There were three sample categories; reference-, tensile test- and thermocouple samples. The investigation included analysis of cooling curves, SinterCast parameters, image analysis, measured hardness and tensile strength. Thermocouples of type N were used at interesting positions for observation of the cooling behaviour and the image analysis was carried out by the software Axio Vision SE64 by Carl Zeiss GmbH. The hardness was measured according to Brinell HBW 5/750 and tensile testing was performed according to standard SS-EN ISO 6892-1:2009.

It is concluded that the microstructure depend on many parameters, one of them is the position in the cylinder block. A relation between solidification time and the microstructure features; secondary dendrite arm spacing and eutectic cell size was observed. Because of dissimilarity in microstructure between the tensile test samples and thermocouple samples it is believed that the thermocouples have contributed with a cooling and/or nucleation effect. Considering the mechanical properties there is not solely the nodularity, eutectic cell size or secondary dendrite arm spacing that are the controlling microstructure feature, more research needs to be made.
1 Introduction

The demand of improved performance for modern diesel engines continues to increase. By increasing the pressure in the combustion chamber, emission and engine performance will be improved. This on the other hand results in more mechanical and thermal load. Currently grey iron with a flake-like graphite structure (LGI) is used as cylinder block material but, as a consequence of future requirements and to avoid increase of size and weight of the engine, either grey iron has to get stronger through different chemical composition or casting processes or another material has to be used. One material candidate for this change is compacted graphite iron (CGI). Due to differences in the microstructure, CGI has different physical and mechanical properties. The tensile strength and stiffness are at least 75% respectively 30-40% higher, and also the fatigue strength is doubled than for conventional LGI.\[1\] Although, the thermal conductivity and mechanical damping is better in LGI than in CGI.\[2\]

For a complex component, like a cylinder block, there are different cooling and solidification rates in different sections. Consequently the mechanical properties will vary.\[1\] Earlier attempts have been done to understand which microstructure feature(s) in CGI that controls the mechanical properties and also investigations for how the microstructure depends on cooling conditions. This was done in order to create a base for predictions of mechanical properties in components.\[3\]

1.1 Purpose

The purpose of this project was to evaluate variations in solidification and cooling rate in compacted graphite iron prototype cylinder blocks and for each position relate this to the microstructure and also relate the microstructure to mechanical properties. This is of interest to increase the knowledge to predict mechanical properties in cast iron components.
2 Cast iron in general

Cast iron is an iron based alloy with a carbon content exceeding 2 wt-%. Industrially used cast iron alloys generally contain 2.5-4.3 wt-% carbon. To achieve specific properties cast iron is, like steel, alloyed. The microstructure of cast iron varies due to differences in composition, solidification time and cooling rate. The most common, phases present in the components, are ferrite or/and pearlite, graphite and cementite. The carbon is either chemically bond as cementite; white iron, or free graphite; grey iron. The outcome can be controlled by the solidification process and composition.\cite{4,5} There are different categories of grey cast iron types and the three most common ones are:

**Lamellar graphite iron (LGI)** which is also known as grey cast iron, picture (a) in Figure 1. The graphite morphology is disc-like with sharp edges, usually described as flake graphite. This was the first discovered graphite cast iron. The widespread term grey iron origins from the appearance of a fractured surface.\cite{4,5}

**Compacted graphite iron (CGI)** is also called vermicular graphite iron, picture (b) in Figure 1. As LGI the graphite is randomly oriented but with rounded edges and the shape is more compact and worm-like with existence of nodules.\cite{4,5}

**Spheroidal graphite iron (SGI)** is also known as ductile cast iron. It has nodular shaped graphite particles, picture (c) in Figure 1.\cite{4,5}

![Figure 1. Graphite morphology for the different cast irons, a. LGI, b. CGI and c. SGI (4).](image)

2.1 Property differences of LGI, SGI and CGI

The flakes in LGI have sharp edges which are the main contributors to the properties; good machinability, good damping properties and good heat conductivity. However the strength is not always satisfying and therefore alloying elements have to be added, but this causes difficulties in castability and machinability. The properties of SGI are instead good strength but low machinability, heat conductivity and damping properties. CGI has properties in between LGI and SGI. Compared to grey iron, CGI has higher strength and ductility and compared to ductile iron, it has better machinability, heat conductivity and damping properties. Due to the vermicular graphite particles, stubby flakes with irregular surface and small amount of nodules, the graphite adhesion to the metal matrix is strong.\cite{6,2}
In Table 1 property differences of pearlitic LGI, CGI and SGI are presented \[7\].

<table>
<thead>
<tr>
<th>Property</th>
<th>LGI</th>
<th>CGI</th>
<th>SGI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile strength [MPa]</td>
<td>250</td>
<td>450</td>
<td>750</td>
</tr>
<tr>
<td>Elastic Modulus [GPa]</td>
<td>105</td>
<td>145</td>
<td>160</td>
</tr>
<tr>
<td>Elongation [%]</td>
<td>0</td>
<td>1.5</td>
<td>5</td>
</tr>
<tr>
<td>Thermal conductivity [W/mK]</td>
<td>48</td>
<td>37</td>
<td>5</td>
</tr>
<tr>
<td>Relative damping capacity</td>
<td>1</td>
<td>0.35</td>
<td>0.22</td>
</tr>
<tr>
<td>R-B fatigue [MPa]</td>
<td>110</td>
<td>200</td>
<td>250</td>
</tr>
</tbody>
</table>

2.2 Nucleation and growth of the microstructure

The solidification process of cast iron covers two phase changes, solidification and then, at about 740°C, solid state transformation of austenite to ferrite or/and pearlite. Composition, cooling rate and inoculation determines if the material solidifies according to the metastable or the stable phase diagram, see Figure 2. During metastable solidification, the carbon is present in cementite (iron carbide Fe₃C). The stable solidification gives graphite.\[^4\],\[^8\],\[^9\]

![Fe-C phase diagram](image)

Figure 2. Fe-C phase diagram, where solid curves represent the stable system iron-graphite and dashed curves represents the metastable system Fe-Fe₃C\[^10\].

In the first step of the solidification process (A) a primary phase is precipitated for example austenite. As the solidification progresses the eutectic temperature is reached and (B) a eutectic structure is formed; graphite eutectic or ledeburite (aus+cem). At the solid state transformation (C) the material matrix changes where austenite transforms to either ferrite or/and pearlite.\[^4\],\[^8\]

---

\[^7\]: Reference 7.

\[^8\]: Reference 8.

\[^9\]: Reference 9.

\[^10\]: Reference 10.
The eutectic reaction takes place at a carbon content of 4.3 wt-%. Each alloying element affects the system differently and therefore the carbon equivalent value (CE) is calculated to understand how different alloying elements affect the casting behaviour and heat treatment, see Equation 1.\(^4\)

\[
CE = \%C + \frac{\%Si}{3} + \frac{\%P}{3}
\]

White solidification, or carbide formation, is promoted if the CE-value is low and the cooling rate is high. If instead the value is high and cooling rate is low grey iron is promoted.\(^11\)

If CE is below 4.3 wt-% carbon the iron melt is hypo-eutectic, like the most commercial cast irons. When the melt solidifies, primary precipitation of austenite dendrites occurs followed by the eutectic reaction. At the eutectic temperature, graphite is precipitated as eutectic cells and either flake graphite or nodules depending on the amount modifying elements, usually magnesium.\(^4\),\(^12\) Mg is added since it neutralize the present O and S who inhibit nodularity\(^13\).

If CE is greater than 4.3 wt-%, i.e. a hypereutectic iron melt, graphite or cementite is primary precipitated followed by the eutectic reaction\(^4\),\(^12\).

When 740°C is reached the second stage of the solidification process begin, solid state transformation with a eutectoid reaction, where the cast iron obtains its room temperature microstructure. Depending on composition, the austenite transforms to pearlite and/or ferrite.\(^14\)

The Fe-C phase diagram shows three possible ways to form graphite particles. Primary precipitated, at the eutectic and if the melt is enriched and undercooled. For the last-mentioned, graphite will be precipitated as many and small graphite particles in the last solidifying melt. This because of segregations which, practically, make the melt hyper-eutectic.\(^10\)

When alloying elements are added they also affect the eutectic temperature which promotes formation of white or grey iron. Additions like chromium, titanium and vanadium decrease the eutectic temperature which promotes formation of white iron. While copper, cobalt, silicon and nickel raise the eutectic temperature and prevent white formation.\(^15\)

When grey solidification is favourable, inoculation is done right before casting.\(^16\) There are several different inoculants for diverse applications for the production of cast iron. The main property is to control the microstructure and mechanical properties by thoughtfully balanced amount of active elements. Some of the elements are rare earth elements, example of elements used are; Aluminium, Barium, Calcium, Cerium, Sulphur and Oxygen, Strontium and Zirconium.\(^17\) These additions forms small crystals by homogeneous nucleation and these crystals acts like nucleation sites for graphite, so called heterogeneities, the mechanism is called heterogeneous nucleation. By increasing the number of nuclei, the cooling area increases due to decrease in growth rate and undercooling.\(^16\) Growth of the formed structure is dependent on movement of the phase boundary between the new and old phase. The growth rate depends on diffusion distance and cooling rate. Graphite growth is favoured by slow cooling and the new graphite builds on the already existing graphite.\(^18\)
2.3  Eutectic cell size (ECS)

The structure formed during eutectic solidification, considering cast iron, is called eutectic cells. In Figure 3 a compacted graphite iron sample has been coloured etched and the eutectic cells are illustrated.\textsuperscript{19}

![Image of eutectic cells](image1.png)

Figure 3. A coloured etched CGI surface showing eutectic cells\textsuperscript{19}.

When the eutectic temperature is reached and one phase has strong anisotropic properties the result is a bad correlation between the phases. The eutectic gets a coarser structure than the regular eutectic structure. Dendrites host the eutectic cells and the cells are developed by cooperation between an austenite crystal and a graphite crystal.\textsuperscript{12} Figure 4 illustrate in 3D the cooperation between eutectic cells and dendrites and also at the top, how the cross section will look like\textsuperscript{20}.

![Image of eutectic cells and dendrites](image2.png)

Figure 4. 3D image of eutectic cells and dendrites\textsuperscript{20}.

The eutectic cells grow radially until they encounter each other and have filled the entire molten volume\textsuperscript{21}. Inoculation favours nucleation and is added to the iron melt to achieve more and smaller eutectic cells\textsuperscript{12}. When a sufficiently large force is applied on a material, it deforms plastically as a result of dislocation movement in the material.

\[ \text{Equation} \]

\[ \text{Equation} \]
Hall-Petch relation states that the yield stress increase with increased grain size, see Equation 2.\[^{[22]}\]

\[
\sigma_y = \sigma_0 + k \gamma d^{-1/2}
\]

Where \(\sigma_y\) is the yield stress, \(\sigma_0\) and \(k\) are constants depending on material and \(d\) stands for the average grain diameter. Therefore every obstacle will constrain the dislocation movement and work as a hardening mechanism resulting in increased yield stress. Smaller and more eutectic cells is therefore believed to results in better mechanical properties due to these stop cracks in the material.\[^{[22]}\]

The appearance of the eutectic differs for the different categories of grey cast irons. For LGI the graphite and austenite grow in contact with the melt and grow radially resulting in a eutectic cell, the austenite and graphite grow cooperatively. In CGI the cooperation between the austenite and graphite differs, it is not as strong as in LGI, although the spherical eutectic cells are formed. However for SGI the austenite encapsulate the graphite nodules creating colonies.\[^{[23]}\]

### 2.4 Secondary dendrite arm spacing (SDAS)

Secondary dendrite arm spacing is a measurement of the space between two so-called secondary dendrite arms, see Figure 5.\[^{[24]}\]

![Figure 5. Image of dendrites and illustration of how the secondary dendrite arm spacing is measured.][1]

During solidification of a hypo-eutectic iron melt dendrites occur as primary precipitated austenite. The secondary dendrite arms are formed immediately behind the growing tip of the primary dendrite arm.\[^{[25]}\] A fine dendrite structure is highly dependent on the cooling rate, increased cooling rate result in fine dendrite structure (decrease in SDAS), and improved mechanical properties.\[^{[14]}\],\[^{[24]}\]. The space between the dendrite arms may have a major influence on the eutectic cell nucleation and growth since the arms act like hosts.\[^{[26]}\]

### 2.5 CGI

In this part CGI is presented regarding acceptable morphology, casting conditions and microstructure formation.

#### 2.5.1 CGI according to international standard

CGI has a stable eutectica with a worm-like shaped graphite.\[^{[27]}\]. To be classified as CGI, according to the ISO (International Organization for Standardization) standard 16112:2006 the microstructure has to contain, on a two dimensional polished surface, at least 80 % compacted shape and less than 20 % with a more round shape and contain no flake graphite. If there is 0 % nodularity one have ideal CGI.
The roundness shape factor (RSF) equation together with image analysis is used to calculate the roundness of the graphite particle, see equation 3 and Figure 6.

\[
\text{Roundness} = \frac{A}{A_m} = \frac{4A}{\pi l_m^2}
\]

eq 3.

Where \(A\) is the area of the graphite particle, \(A_m\) is the area of the circle of diameter \(l_m\) and \(l_m\) is the maximum length of the graphite particle.

The obtained RSF value is evaluated according to Table 2.

<table>
<thead>
<tr>
<th>RSF</th>
<th>Graphite form</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.625-1</td>
<td>Nodular</td>
</tr>
<tr>
<td>0.525-0.625</td>
<td>Intermediate</td>
</tr>
<tr>
<td>&lt; 0.525</td>
<td>Compacted</td>
</tr>
</tbody>
</table>

The different graphite form classifications follow the standard ISO 945; nodular (form VI), intermediate (form IV and V) and compacted (form III). If the maximum length, \(l_m\), of the particle is less than 10 \(\mu m\) the particle is excluded from the calculation.

The nodularity percentage is calculated by Equation 4.

\[
\%\text{Nodularity} = \frac{\sum A_{\text{nodules}} + 0.5 \sum A_{\text{intermediates}}}{\sum A_{\text{all particles}}} \cdot 100
\]

\quad \text{eq 4.}

Where \(A_{\text{nodules}}\) is the area of graphite particles which are classified as nodules, \(A_{\text{intermediates}}\) is the area of graphite particles classified as intermediated formed and \(A_{\text{all particles}}\) is the area of all graphite particles with a length exceeding 10 \(\mu m\).

2.5.2 Casting of CGI

When casting CGI the magnesium content is crucial to control. The companies Novacast, OCC GmbH and Sintercast provide methods to produce CGI. Novacast has a method named ATAS Metstar which is a thermal analysis system consisting of a software and an on-line measuring device, which according to their webpage, evaluate the whole metallurgical process in detail. The company OCC GmbH provides a CGI-navigation process which use thermal analysis for navigation of the whole melt. Sintercast has also an thermal analysis process consisting of a software and an on-line measurement equipment. However the Sintercast process only evaluates the magnesium and inoculant of the base iron and then the necessary amount of magnesium and inoculant are added automatically.

High quality CGI is only stable in a short range of magnesium content. Depending on the charge material for example the purity of the raw graphite material, the range and the so-called stable CGI...
plateau differs considering size and location. It generally has a range of approximately 0.006 % Mg. Figure 7 illustrate the stable range for CGI for a base iron containing 0.010-0.015 % sulphur.[33]

![Graph showing nodularity vs % Total Mg]

**Figure 7.** The yellow lines show the stable range for CGI.[33]

Magnesium alters the graphite morphology which controls the physical properties of the material. If the Mg content is too high nodular graphite is formed which also elaborate risk for porosity defects. If instead the Mg content is to low the graphite will appear as flakes which results in reduced strength. Because of the narrow range, CGI is hard to cast in complex components. The Mg fades at a rate of approximately 0.001 % every five minutes. Therefore, when casting CGI, the initial iron starting point must be far above the CGI-to-grey iron transition to be certain of that flake-like graphite does not form before the end of the pouring.
The Mg fading rate, Mg and S form MgS, is accelerated by the sulphur in the base iron, as sulphur content increases the Mg content decreases. As a result the base iron has to contain less than 0.020 % sulphur. Furthermore, if the sulphur content is too high there is an increased risk for filling defects due to increase in number of sulphide inclusions which cause clogging.[33]

### 2.5.3 Microstructure formation

It is the metallic matrix and the graphite morphology that determine the mechanical properties both at room temperature and at elevated temperatures. The chemical composition, inoculation level and the section thickness are the factors that mainly influence the metallic matrix and graphite morphology.[2]

#### 2.5.3.1 Solidification

According to the Fe-C phase diagram, see Figure 2, if the melt is hypo-eutectic the solidification starts with precipitation of austenite dendrites (primary phase). A hypo-eutectic composition is preferred when casting CGI. The primary dendrite arm often initiates at the mould wall or nucleate on heterogeneities in the melt, resulting in columnar respectively equiaxed growth. The dendrites continue to grow until they meet and encounter each other and starts go through coarsening. As the dendrites grow the composition changes, following the solidus line in the phase diagram (if equilibrium), where carbon is emitted to the metal melt. If the diffusion of carbon is too slow, segregations will be emerged which result in more carbon in the last solidifying melt.[13]
The other alloying elements will also segregate. The alloying elements in cast iron that segregate to the last solidifying melt are Mn, Mo, Cr and Mg and for the solid phase Si and Cu. Segregation can be described by a partition coefficient, $K$, see Equation 5.[13]

\[
K = \frac{C_s}{C_l} \tag{5}
\]

Where $C$ is the concentration of the alloying element in solid respectively liquid. For elements in the last solidifying melt $K<1$ and for elements in the first solidifying area $K>1$.[13]

When the eutectic temperature is reached and there is some undercooling, the eutectic structure is initiated. The graphite grows as eutectic cells and they are developed by cooperation between austenite crystals and graphite crystals. The graphite shape is the main contribution to the mechanical properties. Graphite has a hexagonal close packed lattice, see Figure 8.[13]

![Figure 8. The hexagonally close packed lattice of graphite][34]

For CGI the graphite grows along both the a- and c-axis directions while for LGI and SGI the graphite growth direction is only along the a-axis respectively c-axis. During solidification, the graphite structure is dependent on the cooling rate and composition of the iron.[13]

### 2.5.3.2 Solid state transformation

The iron matrix changes during the solid state transformation. Depending on cooling rate and chemical composition the austenite transforms to ferrite or/and pearlite. For the stable iron-graphite system with only Fe and C present the eutectoid temperature is about 740°C. The temperature is changed by alloying elements as for example silicon. When the eutectoid temperature is reached a ferrite matrix will be formed because the carbon diffuses away from the ferrite-austenite-surface to the graphite. The newly formed ferrite surrounds the graphite like a shell (degenerated eutectoid reaction) because it is nucleated on the a-axis edges of the graphite particles this since it is energetically more favourable for carbon atoms.[35]
The a-axis direction in graphite nodules is tangential and therefore the ferrite growth occurs around the nodule forming a shell. For LGI the a-axis direction is along the flake and the ferrite only forms at the edges of the flakes, see Figure 9.\textsuperscript{35}

\begin{figure}
\centering
\includegraphics[width=0.5\textwidth]{figure9.png}
\caption{Differences of ferrite growth depending on graphite direction\textsuperscript{35}.}
\end{figure}

The ferrite reaction is soon inhibited due to the pearlite reaction which starts at the metastable eutectoid transformation temperature, which is according to the metastable Fe-Fe\textsubscript{3}C system about 727°C\textsuperscript{14,35}. This temperature is also changed by alloying elements. The diffusion distance for carbon is shorter in pearlite, the carbon in ferrite diffuses to the cementite, than for carbon diffusion from austenite to graphite.\textsuperscript{35} The excess carbon in the matrix and iron are bond together which result in cementite plates, and pearlite is obtained\textsuperscript{36}. Pearlite morphology is lamellar, at low undercooling the lamellar spacing increase due to fast diffusion. If high undercooling, low temperature, the lamella’s obtain a fine structure due to slow diffusion.\textsuperscript{37}

There is a significant difference between the mechanical properties if a ferrite matrix or a pearlite matrix is obtained\textsuperscript{35}.

\subsection*{2.5.3.3 Alloying elements}

The obtained microstructure is dependent of the chemical composition. The commonly used alloying elements are copper (Cu), tin (Sn), manganese (Mn), chromium (Cr), magnesium (Mg) and silicon (Si). Each element influences the solidified microstructure in different ways.\textsuperscript{13,35}

Pearlite promoting elements are Cu and Sn. These elements will act as diffusion barriers, making carbon diffusion from austenite to graphite harder. The alloying elements Mn and Cr increase the solubility of carbon in austenite resulting in more cementite formation during the solid state transformation from austenite to ferrite/pearlite. Sulphur and manganese form MnS which potentially enables good machinability. Si promotes ferrite formation. Mg is added to the melt to change the graphite morphology.\textsuperscript{35}
2.5.4 Cooling curve for CGI

To understand the solidification process; precipitation and growth of phases in CGI, thermal analysis can be made, with thermocouples. The liberated heat is shown in a cooling curve.\[23\] The general appearance of such curve is shown in Figure 10, the phase transformations are marked \[13\].

![Figure 10. General cooling curve of CGI where the two main phase transformations are marked.](image)

The behaviour for the first part of the cooling curve, when the austenite starts to form, is due to the liberated heat from the austenite which makes a plateau. The decrease in temperature, between the austenite precipitation and eutectic transformation, is due to the austenite dendrites has encountered each other and began to coarsen. At the point where it is enough undercooling for the carbon atoms to be extracted from the liquid the eutectic reaction starts. By adding inoculant the necessary undercooling is decreased. This is followed by recalescence (curve go up), where the carbon is consumed by the graphite and both graphite and austenite grow and the austenite liberate heat.\[23\] This is followed by a decrease in temperature and then the solid state transformation begins. Again the arrest in the cooling curve is due to evolved heat when ferrite and pearlite forms, some undercooling is needed and then there is some recalescence.\[35\]

2.6 Standard casting process for CGI cylinder blocks

The production chain for casting CGI cylinder blocks include the manufacturing of the core and the mould, melting, casting, cooling storage and finally the shaking out part. Since the final properties and quality of the cylinder block are influenced of the different stages in the production, the knowledge of all the involved parameters and variables are important.\[38\]
2.6.1 Core
The interior geometry of the cylinder block is obtained by the core \cite{39}. The key elements of the core are a mixture of sand and a binder, see Table 3 \cite{40}.

<table>
<thead>
<tr>
<th>Core</th>
<th>Sand</th>
<th>Binder</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Råda 85%, Zr-sand 15%</td>
<td>Coldbox (Fenolharts+isocyanat+amin)</td>
</tr>
<tr>
<td>Core</td>
<td>Brogård</td>
<td>Vattenglas (Na2O-SiO2-H2O)</td>
</tr>
</tbody>
</table>

During manufacturing the mixture is placed in a box, where the inside has the same shape as the desired core, the mixture is then compacted \cite{39}. The core strength is obtained when the chemical binder cures in the sand. To prevent chemical reactions between the core and molten iron, through pores and other surface defects, the exposed areas are painted with a thin coating.\cite{38}

2.6.2 Mould
The mould has a so-called mould cavity which represent the hollow space with the desired external shape and geometry of the cylinder block \cite{39}. The pouring basin, venting system, inlet and gating system for the molten metal are also included in this part. The sand mixture consisting of sand and the binder bentonite is shot into a steel flask and pressed against a pattern.\cite{38} See Table 4 for chemical composition of the mould \cite{40}.

<table>
<thead>
<tr>
<th>Sand</th>
<th>Bentonite</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recycled core and a small amount of new sand from Brogård</td>
<td>Al2O3-4SiO2-H2O, is a mineral containing montmorillonit with the formula (Na, Ca)0,3(Al, Mg)2Si4O10(OH)2-nH2O. Bentonite can contain potassium.</td>
</tr>
</tbody>
</table>

The flask consists of two parts, an upper part and a lower part. To avoid mould erosion during casting the lower part is sprayed with a thin coating layer \cite{38}.

2.6.3 Assembling and casting
Core, mould and Al2O3 filters are assembled and prepared for metal pouring \cite{38}. The induction furnace is charged with iron scrap and after melting, the chemical composition is controlled before tapping into smaller ladles. For the base treatment the ladle is charged with FeSiMg and to avoid that the magnesium reacts too fast with the iron, six kilograms steel chips is covering the base treatment addition. Then the inoculant Foundrisil and CeMM also called mischmetal (Cerium and lanthanum) is added. Foundrisil is silicon based ferroalloys containing calcium and barium.\cite{41} The base iron is tapped into the ladle and the temperature is measured. During the base treatment the active oxygen and sulphur is consumed. Magnesium reacts with oxygen and form MgO however later Mg forms MgS and therefore CeMM is added which reacts with S forming CeS which is more stable than MgS.\cite{42} The melt is analyzed with the Sintercast process and then, if required, extra magnesium and inoculant wire is added before pouring into the mould \cite{33}.
2.6.3.1 Sintercast process
After the base treatment a sample of the melt is collected and the Sintercast sampling cup is filled, see Figure 11 [33].

![Image of a Sintercast sampling cup within a red circle.](image)

Figure 11. The Sintercast sampling cup is within the red circle [33].

The cup is used for measurement of modification index (MGM), inoculation index (MGI) and carbon equivalent (CE) by thermal analysis. MGM is for the Mg and other alloys and MGI is for the inoculant. The measured values for respectively MGM, MGI and CE, if acceptable or not, are shown on a screen. If some Mg and inoculant is needed, a wire feeder adds the correct amount automatically. In order to know the Mg-fade rate the walls of the sampling cup are coated with a reactive coating which simulate the fading of magnesium. This ensures that the modification is high enough and therefore no risk for flake graphite formation but not too high which prevent the risk for porosity defects.[33]

2.6.4 Cooling
The cast cylinder block is transported to a storage area where it is pressed out from the flask and then left to cool down in the sand mould to eliminate risk of shape changes and residual stresses [38].

2.6.5 Shaking out
When the block has reached low enough temperature the sand and other unwanted parts are separated from the cylinder block. The sand is separated by a shaker, the block is then collected and the in-gates, pouring basin etcetera are removed. The cylinder block goes through further cleaning before it either ends up in storage or is passed on to the next step and finally ends up in the truck.[38]

2.6.6 Chemical composition
The chemical composition of cast CGI 400 should be in accordance with the following [43]:

<table>
<thead>
<tr>
<th></th>
<th>C [wt-%]</th>
<th>Si [wt-%]</th>
<th>Mn [wt-%]</th>
<th>S [wt-%]</th>
<th>Mg [wt-%]</th>
<th>CeMM [wt-%]</th>
<th>Cu [wt-%]</th>
<th>Sn [wt-%]</th>
<th>CE [wt-%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>min</td>
<td>3.60</td>
<td>2.1</td>
<td>0.2</td>
<td>0.005</td>
<td>0.006</td>
<td>0.01</td>
<td>0.3</td>
<td>0.03</td>
<td>4.4</td>
</tr>
<tr>
<td>max</td>
<td>3.80</td>
<td>2.5</td>
<td>0.4</td>
<td>0.022</td>
<td>0.014</td>
<td>0.03</td>
<td>0.6</td>
<td>0.05</td>
<td>4.7</td>
</tr>
</tbody>
</table>

Table 5. Chemical composition guidelines for CGI 400 [43].
3 Experimental procedure

This chapter includes information about the used equipment, preparation of the sand core and mould, positions of the thermocouples and the analytic approach of the microstructure and mechanical properties. To briefly study the influence of the treatment and the inoculation, some samples from previous CGI castings were investigated in aspects of microstructure, tensile strength and SinterCast parameters. These specimens are from now on called reference samples. Also tensile test samples (TT-samples), from the present casting, corresponding to the thermocouple positions was investigated.

3.1 Used equipment
3.1.1 Thermocouples
Thermocouples are instruments for temperature measurements by thermal analysis. Thermocouples consist of two wires of dissimilar metallic materials which has different Seebeck coefficients (magnitude of the induced voltage). When the thermocouple is exposed to temperature, the different wires generates different voltage and this voltage difference is measured.\[^{[44]}\] Each temperature represent a mV value. For type N (with Nicrosil-Nisil as thermocouple alloys), the voltage range for temperatures between 0-1300 °C is 0-47.513 mV with a non-linear behaviour.\[^{[45]}\] To be able to use thermocouples at high temperatures they are protected by a metal shell. For insulation of the wires, heavily compressed magnesia (MgO) is used inside the shell.\[^{[46]}\]

The used thermocouples in this master thesis were of type N and the used length was 2.5 and 5 meters with a diameter of 1.5 mm. The thermocouple wires were protected by a inconel metal shell and ended with a standard connector. Additionally, for further protection at more exposed positions, the thermocouples were wrapped with inconel casings.

3.1.2 PC-logger and software
A PC-logger is a measuring instrument for different applications, in this case for temperature measurements.\[^{[47]}\] The logger’s function is to register the measured voltage and transmitted them to a computer. In this case the used software was Easyview 5.6 where the output is temperature as a function of time. The input values for the logger was to log alternate seconds and take a mean value of two values. The temperature was assumed to never exceed 1300 °C (corresponding to 47.513 mV), therefore 50 mV T/C was set for each channel.

3.2 Preparation of cylinder blocks
Two prototype cylinder blocks with 12 thermocouples each were prepared. This to assure a result and for statistics since the high temperatures induce a substantial risk for the experiment.
3.2.1 Position of thermocouples

The position for each thermocouple was based on a previous experiment but with some differences. The temperature was measured either in the core, the iron or the sand mould. Table 6 give an overview of the positions [38].

Table 6. Position for each thermocouple [38].

<table>
<thead>
<tr>
<th>Name</th>
<th>Material/placement</th>
<th>Solidification/cooling condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>Sand core (Water jacket)</td>
<td></td>
</tr>
<tr>
<td>C2</td>
<td>Sand core (Water jacket)</td>
<td></td>
</tr>
<tr>
<td>C3</td>
<td>Iron</td>
<td>Fast solidification, fast cooling</td>
</tr>
<tr>
<td>C4</td>
<td>Iron (Partition wall 4)</td>
<td>Slow solidification, slow cooling</td>
</tr>
<tr>
<td>C5</td>
<td>Iron (Partition wall 4)</td>
<td>Slow solidification, slow cooling</td>
</tr>
<tr>
<td>C6</td>
<td>Iron (Partition wall 3)</td>
<td>Fast solidification, slow cooling</td>
</tr>
<tr>
<td>C7</td>
<td>Sand core (Water jacket)</td>
<td></td>
</tr>
<tr>
<td>C8</td>
<td>Iron (front of block )</td>
<td>Fast solidification, fast cooling</td>
</tr>
<tr>
<td>C9</td>
<td>Iron (Partition wall 3)</td>
<td>Fast solidification, slow cooling</td>
</tr>
<tr>
<td>C10</td>
<td>Sand mould</td>
<td></td>
</tr>
<tr>
<td>C11</td>
<td>Sand mould</td>
<td></td>
</tr>
<tr>
<td>C12</td>
<td>Sand mould</td>
<td></td>
</tr>
</tbody>
</table>

For an overview of where the thermocouples were placed in the cylinder block see Figure 12-15.

![Figure 12. Overview of thermocouples placed in the iron.](image)
Figure 13. Partition wall 4, placement of thermocouples C4 and C5. The blue line represents the center of the cylinders.

Figure 14. Partition wall 3, position of thermocouples C6 and C9. The blue line represents the center of the cylinders.

Figure 15. Thermocouple C8 placed in wall 1.
3.3 Cooling curve analysis

The derivate for each cooling curve was used for determination of the liquidus temperature, solidus temperature, solidification time, solid state transformation temperature, time for pearlite transformation, the time for all phase transformations to end and cooling rate at 750 °C and 700 °C. The measured temperatures are marked in the cooling curve and time is measured according to Figure 16.

![Cooling curve analysis diagram](image)

**Figure 16.** Temperature curve of thermocouple five and the measured time is specified.

The intervals \( t_{\text{solidification}} \) and \( t_{\text{pearlite}} \) describes the time for solidification and solid state transformation.

Figure 17 and 18 are examples of how the temperatures were obtained for thermocouple C5.

![Thermocouple 5](image)

**Figure 17.** The derivate as a function of time (32 min) for thermocouple five. \( T_L \) stands for liquidus temperature and \( T_S \) is for solidus temperature.
Figure 18. The derivate as a function of time for the entire temperature range of thermocouple five. $T_L$ stands for liquidus temperature and $T_S$ is for solidus temperature.

For simplicity, the last minimum has been used since the point for when solid state transformation ends is hard to distinguish.

3.4 Metallographic examination

This part describes the image analysis of the samples with enclosed thermocouples, from now on called the TC-samples, and the reference samples and tensile testing samples. The software Axio Vision SE64 by Carl Zeiss GmbH was used to study average eutectic cell size (paragraph 2.3), nodularity, average secondary dendrite arm spacing (paragraph 2.4), the intercellular part, the pearlite lamellar distance and ferrite content.

For the graphite analysis, the study of average eutectic cell size, average secondary dendrite arm spacing and the intercellular part the program module Mosaiq was used to create a representation of the whole sample, one image was created of many and small images. For the reference samples a 70.74 mm$^2$ image consisting of 7x8 images with a 100X magnification was made covering the whole sample. While for the TC-samples an image was taken as close to the thermocouple as possible. Creating a 32.039 mm$^2$ image consisting of 5x5 images with a 100x magnification. For the tensile test samples an area of 20.86 mm$^2$ was created.

3.4.1 Graphite analysis

The program module Graphite calculation from Carl Zeiss GmbH was used for the graphite analysis. The program measures the graphite shape and size and uses the standard ISO16112:2006 for the calculations. Also the amount of nodules was calculated.

3.4.2 AECS, SDAS and intercellular part analysis

3.4.2.1 Colour etching

Colour etching was performed on all the samples as preparation for the image analysis when average ECS, average SDAS and the intercellular part would be evaluated. Colour etching is made to create a stable thin film on the sample surface which creates an optical interference effect [48]. The silicon in the sample will react with the etchant and transform into a SiO$_2$ film. When the thickness of the film increases colours occur. The colours depend on the segregation pattern of silicon [49]. The areas which
have high silicon content ranges from white to light blue and to deep blue. The areas with low silicon content have a light yellowish-brown colour.\cite{13}

For this experiment a colour etchant with the composition of 400 ml picric acid solution and 100 g NaHo was used since it is a well studied recipe according to Scania in-house. The specimens were held in a basket, one at a time, at a temperature range of 78-90 °C and were etched for 8-25 min. Then rinsed with water and ethanol. Figure 19 show the experimental setup.

Figure 19. Experimental setup for colour etching.
3.4.2.2 Image analysis

For the average eutectic cell size ten representative cells were chosen. An mean value of the diameter for the largest cells was calculated and then used to calculate the mean value for all cells, see Figure 20.

![Figure 20. Illustration of how the average eutectic cell size was measured.](image)

The average SDAS was measured and calculated as a mean value for ten representative secondary dendrite spacing’s, measured from centre to centre, see Figure 21.

![Figure 21. Illustration of how the SDAS was measured.](image)

The intercellular part of each sample was achieved by calculate the amount of eutectic cells. First the cells that do not cut the edge of the image was calculated, see Equation 6.

\[
\text{cell\%} = \frac{(A_m \cdot N_i)}{A_{tot}} \times 10^{-6}
\]

Where \(A_m\) is the average cell area, \(N_i\) is number of cells inside image and \(A_{tot}\) is the total area of the analysed image.
Figure 22 show an illustration of how cells were marked.

![Figure 22. Example, zoomed area of cells market inside image, where the bold red circle illustrates a cell.](image)

By include the cells that intersect the edge into the calculation the total area of cells was obtained, see Equation 7.

$$\text{All cell\%} = \frac{\left( A_m N_i + (A_m N_{\text{edge}} p) \right)}{A_{\text{tot}}} \times 10^6$$  

Where \(N_{\text{edge}}\) is number of cells that intersect the edge, \(p\) is an estimation of how much can be seen of the cells that intersect the edge and \(A_{\text{tot}}\) is the total area of the analysed image. Figure 23 show how the cells at the edge of the image were marked.

![Figure 23. Example, zoomed area where the bold red circle illustrate a cell that cut the edge.](image)

### 3.4.3 Pearlite and ferrite analysis

#### 3.4.3.1 Nital etching

The pearlite lamellar distance and ferrite content was calculated on nital etched samples. The used nital etchant was 2 % nital (mixture of nitric acid and ethanol). The samples were etched until the microstructure became visible (few seconds), then washed with plenty of water and finally with ethanol.
3.4.3.2 Image analysis
The closest pearlite lamellas was evaluated since there can be differences in the cross section area. Each sample was evaluated in five different areas. The reference samples were evaluated in each corner and the middle of the sample. The same for the TC- and TT-samples but in the same area as the previous Mosaiq images were taken. For each position a mean value of ten lamellas was calculated, see Figure 24, this mean value was then used to calculate a representative value for the whole sample.

![Figure 24. Distance of ten pearlite lamellas, 1000X magnification.](image)

To measure the ferrite content two samples were selected, the one with the highest ferrite content and the one with the lowest. For the reference samples five images were taken of both samples with a magnification of 100X. While for TC- and TT-samples a Mosaiq image was made for both samples. The program module Graphite analysis by Carl Zeiss GmbH was used to approximate the amount of light areas and to calculate a mean value.

3.5 Hardness
The hardness was measured according to Brinell HBW 5/750. A hardmetal ball with a 2.5 mm diameter was forced for 12 s into the surface of a test piece. After removal, the diameter of the indent was measured. A mean value of five hardness indents was calculated on the TC-samples and one indent was made on the tensile test samples.

3.6 Mechanical properties
Tensile testing was performed according to standard SS-EN ISO 6892-1:2009. The sample was rigged in a tension machine, were the ends are fixed. The sample was then exposed to tension until failure and the measured tensile strength is the maximum stress the sample sustains without fracture. The tensile tests were taken from positions corresponding to the thermocouple positions, in the same cylinder block but in different walls.
4 Results

4.1 Chemical composition

Table 7 show the composition of the melt, the sample was taken from the ladle.

Table 7. Obtained chemical composition of cast cylinder blocks in wt-%.

<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>Ni</th>
<th>Al</th>
<th>Cu</th>
<th>Nb</th>
<th>Ti</th>
<th>V</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3.748</td>
<td>1.89</td>
<td>0.192</td>
<td>0.035</td>
<td>0.013</td>
<td>0.014</td>
<td>0.015</td>
<td>&lt;0.010</td>
<td>0.005</td>
<td>0.888</td>
<td>0.004</td>
<td>0.014</td>
<td>0.003</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Pb</th>
<th>Sn</th>
<th>Mg</th>
<th>As</th>
<th>Ce</th>
<th>La</th>
<th>N</th>
<th>Fe</th>
<th>Cekv</th>
<th>Co</th>
<th>Zr</th>
<th>Zn</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.001</td>
<td>0.059</td>
<td>0.009</td>
<td>&lt;0.001</td>
<td>0.033</td>
<td>0.014</td>
<td>0.004</td>
<td>93,039</td>
<td>4,238</td>
<td>&lt;0.005</td>
<td>&lt;0.001</td>
<td>0.001</td>
<td></td>
</tr>
</tbody>
</table>

Compared with the guidelines for the composition there is less of Si and Mn and also more of Cu and Sn.

Two pieces one for each cylinder block with thermocouples was analysed, see Table 8. The analyse was carried out at an external laboratory, D-lab.

Table 8. Chemical composition for the first and last cast cylinder block.

<table>
<thead>
<tr>
<th>Element</th>
<th>Composition [wt-%] for the first cylinder block</th>
<th>Composition [wt-%] for the last cylinder block</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>3.70 +/- 0.07</td>
<td>3.65 +/- 0.07</td>
</tr>
<tr>
<td>Si</td>
<td>1.99 +/- 0.06</td>
<td>2.01 +/- 0.07</td>
</tr>
<tr>
<td>Mn</td>
<td>0.17 +/- 0.004</td>
<td>0.18 +/- 0.004</td>
</tr>
<tr>
<td>P</td>
<td>0.039 +/- 0.004</td>
<td>0.041 +/- 0.004</td>
</tr>
<tr>
<td>S</td>
<td>0.015 +/- 0.002</td>
<td>0.012 +/- 0.002</td>
</tr>
<tr>
<td>Cr</td>
<td>0.03 +/- 0.004</td>
<td>0.03 +/- 0.004</td>
</tr>
<tr>
<td>Ni</td>
<td>0.02 +/- 0.002</td>
<td>0.02 +/- 0.002</td>
</tr>
<tr>
<td>Mo</td>
<td>&lt;0.02 +/- 0.0007</td>
<td>0.04 +/- 0.001</td>
</tr>
<tr>
<td>Ti</td>
<td>0.014 +/- 0.0004</td>
<td>0.014 +/- 0.0004</td>
</tr>
<tr>
<td>Cu</td>
<td>0.92 +/- 0.01</td>
<td>0.91 +/- 0.01</td>
</tr>
<tr>
<td>Co</td>
<td>&lt;0.02 +/- 0.0004</td>
<td>&lt;0.02 +/- 0.0004</td>
</tr>
<tr>
<td>N</td>
<td>0.004</td>
<td>0.004</td>
</tr>
<tr>
<td>Sn</td>
<td>0.051 +/- 0.001</td>
<td>0.053 +/- 0.001</td>
</tr>
<tr>
<td>W</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>V</td>
<td>&lt;0.01 +/- 0.001</td>
<td>&lt;0.01 +/- 0.001</td>
</tr>
<tr>
<td>Al</td>
<td>0.003</td>
<td>0.003</td>
</tr>
<tr>
<td>B</td>
<td>&lt;0.001 +/- 0.00007</td>
<td>&lt;0.001 +/- 0.00007</td>
</tr>
<tr>
<td>Mg</td>
<td>0.010</td>
<td>&lt;0.010</td>
</tr>
</tbody>
</table>

The first cast cylinder block (61) have more S and Mg but less Mo than the last cast cylinder block (65).
4.2 Thermocouple positions

To be able to distinguish the final position of all thermocouples, each wall with enclosed thermocouples was cut out with a thickness of 11 mm and investigated with transmitting radioscopy (x-ray). In Figure 25 a thermocouple is illustrated.

![Figure 25. Thermocouple inside the wall.](image)

The thermocouples were almost at the original positions, the maximum measured difference was 15 mm.
4.3 Cooling curves

Table 9 shows the results from the cooling curves calculations for the first cast cylinder block (block 61). Where r is the distance to nearest wall, measured from original positions.

<table>
<thead>
<tr>
<th>Thermocouple</th>
<th>Temp [°C]</th>
<th>Solidification time</th>
<th>Cooling rate at 750 °C [°C/min]</th>
<th>Cooling rate at 700 °C [°C/min]</th>
<th>Time for solid state transformation</th>
<th>Total time for phase transformations</th>
</tr>
</thead>
<tbody>
<tr>
<td>C3 r=4mm</td>
<td>TL = 1142 TSL = 1096</td>
<td>2min 4s</td>
<td>2.16</td>
<td>0.98</td>
<td>55min 35s</td>
<td>1h 58min 40s</td>
</tr>
<tr>
<td>C4 r=12mm</td>
<td>TL = 1154 TSL = 1069</td>
<td>16min</td>
<td>1.46</td>
<td>1.042</td>
<td>50min 35s</td>
<td>2h 7min 14s</td>
</tr>
<tr>
<td>C5 r=18mm</td>
<td>TL = 1153 TSL = 1110</td>
<td>15min 16s</td>
<td>1.133</td>
<td>1.5</td>
<td>1h 17min</td>
<td>2h 47min 16s</td>
</tr>
<tr>
<td>C6 r=7.5mm</td>
<td>TL = 1147 TSL = 1110</td>
<td>6min 28s</td>
<td>2.15</td>
<td>0.94</td>
<td>29min 26s</td>
<td>1h 28min 32s</td>
</tr>
<tr>
<td>C8 r=7mm</td>
<td>TL = 1174 TSL = 1122</td>
<td>3min 10s</td>
<td>10.81</td>
<td>2.22</td>
<td>10min 42s</td>
<td>48min 32s</td>
</tr>
<tr>
<td>C9 r=12mm</td>
<td>TL = 1148 TSL = 1127</td>
<td>3min 37s</td>
<td>2.36</td>
<td>0.92</td>
<td>26min 44s</td>
<td>1h 25min 50s</td>
</tr>
</tbody>
</table>
The result for each thermocouple position in the last cast cylinder block (block 65) can be seen in Table 10. Where r is the distance to nearest wall measured from original positions.

### Table 10. Result of cooling curves for block 65.

<table>
<thead>
<tr>
<th>Thermocouple</th>
<th>Temp [°C]</th>
<th>Solidification time</th>
<th>Cooling rate at 750 °C [°C/min]</th>
<th>Cooling rate at 700 °C [°C/min]</th>
<th>Time for solid state transformation</th>
<th>Total time for phase transformations</th>
</tr>
</thead>
<tbody>
<tr>
<td>C3 r=4mm</td>
<td>T_l = 1142, T_s = 1096, T_p, start = 734, T_p, end = 680</td>
<td>2min 8s</td>
<td>2.22</td>
<td>0.92</td>
<td>51min 20s</td>
<td>1h 39min 20s</td>
</tr>
<tr>
<td>C4 r=12mm</td>
<td>T_l = T_s = T_p, start = 743, T_p, end = 709</td>
<td>-</td>
<td>1.75</td>
<td>1.133</td>
<td>45min 26s</td>
<td>-</td>
</tr>
<tr>
<td>C5 r=18mm</td>
<td>T_l = T_s = T_p, start = 750, T_p, end = 707</td>
<td>-</td>
<td>1.298</td>
<td>1.39</td>
<td>1h 14min 48s</td>
<td>-</td>
</tr>
<tr>
<td>C6 r=7.5mm</td>
<td>T_l = T_s = T_p, start = 740, T_p, end = 716</td>
<td>-</td>
<td>2.247</td>
<td>1</td>
<td>29min 56s</td>
<td>-</td>
</tr>
<tr>
<td>C8 r=7mm</td>
<td>T_l = T_s = T_p, start = 734, T_p, end = 702</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>C9 r=12mm</td>
<td>T_l = 1151, T_s = 1116, T_p, start = 730, T_p, end = 713</td>
<td>3min 36s</td>
<td>2.86</td>
<td>1.07</td>
<td>24min 20s</td>
<td>1h 20min 14s</td>
</tr>
</tbody>
</table>

For the first cast cylinder block (61) thermocouple position C4 has the longest solidification time while C3 has the shortest. Position C8 has the highest cooling rate at both 750 °C and 700 °C and also the shortest time for solid state transformation.

For the last cast cylinder block (65) few calculations could be made due to disturbances in the cooling curves.

### 4.4 Microstructure

Table 11 show the result from the image analysis of the cast blocks (61 and 65) with thermocouples.

### Table 11. Result microstructure analysis for TC-samples.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Nodularity [%]</th>
<th>Average ECS [µm]</th>
<th>Average SDAS [µm]</th>
<th>Intercellular part [%]</th>
<th>Lamellar distance [µm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>TC61C3*</td>
<td>23</td>
<td>302</td>
<td>21</td>
<td>60</td>
<td>0.4</td>
</tr>
<tr>
<td>TC 61C4</td>
<td>12</td>
<td>763</td>
<td>39</td>
<td>35</td>
<td>0.4</td>
</tr>
<tr>
<td>TC 61C5</td>
<td>12</td>
<td>1074</td>
<td>50</td>
<td>47</td>
<td>0.4</td>
</tr>
<tr>
<td>TC 61C6</td>
<td>21</td>
<td>468</td>
<td>37</td>
<td>56</td>
<td>0.4</td>
</tr>
<tr>
<td>---------</td>
<td>----</td>
<td>-----</td>
<td>----</td>
<td>----</td>
<td>-----</td>
</tr>
<tr>
<td>TC 61C8</td>
<td>13</td>
<td>600</td>
<td>27</td>
<td>49</td>
<td>0.4</td>
</tr>
<tr>
<td>TC 61C9</td>
<td>12</td>
<td>398</td>
<td>28</td>
<td>49</td>
<td>0.4</td>
</tr>
<tr>
<td>TC 65C3*</td>
<td>25</td>
<td>240</td>
<td>24</td>
<td>72</td>
<td>0.4</td>
</tr>
<tr>
<td>TC 65C4</td>
<td>13</td>
<td>597</td>
<td>48</td>
<td>50</td>
<td>0.5</td>
</tr>
<tr>
<td>TC 65C5</td>
<td>16</td>
<td>1104</td>
<td>47</td>
<td>42</td>
<td>0.5</td>
</tr>
<tr>
<td>TC 65C6</td>
<td>21</td>
<td>351</td>
<td>56</td>
<td>55</td>
<td>0.5</td>
</tr>
<tr>
<td>TC 65C8</td>
<td>18</td>
<td>268</td>
<td>60</td>
<td>60</td>
<td>0.4</td>
</tr>
<tr>
<td>TC 65C9</td>
<td>15</td>
<td>349</td>
<td>54</td>
<td>52</td>
<td>0.5</td>
</tr>
</tbody>
</table>

*Not evaluated right beside thermocouple.

For both cylinder blocks the nodularity and intercellular part was highest in position C3 and the average ECS was largest at position C5. The average SDAS was largest in position C5 for block 61 while for block 65 SDAS was largest in position C8. The lamellar distance had small differences.

The ferrite content was, for both cylinder blocks, highest in position C3 and lowest at position C6. The average ferrite amount was approximately 6 % and 2 %.

The carbide content was within the normal ranges, which are very low, less than 1 %.
Examples of the microstructure are illustrated in Figure 26-28. In Figure 26 the graphite is seen as nodules and stubby flakes.

Figure 26. Graphite analyze image for sample 61C4.

Figure 27 shows a colour etched sample were the eutectic cells, nodules and secondary dendrite arms are seen.

Figure 27. Thermocouple 61C5 colour etched.
A nital etched sample is shown in Figure 28, the ferrite (white) and pearlite is visible.

Figure 28. Thermocouple 65C6 nital etched.

The results for the tensile test samples microstructure is shown in Table 12.

Table 12. Microstructure result of image analysis for TT-samples.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Nodularity [%]</th>
<th>Average ECS [µm]</th>
<th>Average SDAS [µm]</th>
<th>Intercellular part [%]</th>
<th>Lamellar distance [µm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>TT61C3</td>
<td>14</td>
<td>432</td>
<td>50</td>
<td>0,4</td>
<td></td>
</tr>
<tr>
<td>TT61C4</td>
<td>9</td>
<td>547</td>
<td>45</td>
<td>0,4</td>
<td></td>
</tr>
<tr>
<td>TT61C5</td>
<td>14</td>
<td>704</td>
<td>59</td>
<td>0,5</td>
<td>0,4</td>
</tr>
<tr>
<td>TT61C6</td>
<td>20</td>
<td>326</td>
<td>53</td>
<td>0,4</td>
<td></td>
</tr>
<tr>
<td>TT61C8</td>
<td>16</td>
<td>465</td>
<td>45</td>
<td>0,4</td>
<td></td>
</tr>
<tr>
<td>TT61C9</td>
<td>16</td>
<td>594</td>
<td>49</td>
<td>0,4</td>
<td></td>
</tr>
<tr>
<td>TT65C3</td>
<td>11</td>
<td>459</td>
<td>44</td>
<td>0,4</td>
<td></td>
</tr>
<tr>
<td>TT65C4</td>
<td>8</td>
<td>640</td>
<td>39</td>
<td>0,5</td>
<td></td>
</tr>
<tr>
<td>TT65C5</td>
<td>13</td>
<td>940</td>
<td>46</td>
<td>0,4</td>
<td></td>
</tr>
<tr>
<td>TT65C6</td>
<td>17</td>
<td>325</td>
<td>30</td>
<td>0,4</td>
<td></td>
</tr>
<tr>
<td>TT65C8</td>
<td>9</td>
<td>473</td>
<td>31</td>
<td>0,4</td>
<td></td>
</tr>
<tr>
<td>TT65C9</td>
<td>13</td>
<td>745</td>
<td>36</td>
<td>0,4</td>
<td></td>
</tr>
</tbody>
</table>

For both cylinder blocks the nodularity and intercellular part was highest in position C6 and the average ECS was largest at position C5. The average SDAS was hard to see in some samples, therefore lack of results. The lamellar distance had little variation.

The average ferrite amount was approximately 2 % and 7 % for position C6 respectively C3.
The image analysis result of the reference samples is shown in Table 13.

Table 13. Microstructure result of image analysis for reference samples.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Nodularity [%]</th>
<th>Average ECS [µm]</th>
<th>Average SDAS [µm]</th>
<th>Intercellular part [%]</th>
<th>Lamellar distance [µm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1 V2</td>
<td>13</td>
<td>692</td>
<td>36</td>
<td>46</td>
<td>0.4</td>
</tr>
<tr>
<td>H2</td>
<td>11</td>
<td>806</td>
<td>56</td>
<td>49</td>
<td>0.5</td>
</tr>
<tr>
<td>R2 V4</td>
<td>11</td>
<td>689</td>
<td>37</td>
<td>41</td>
<td>0.4</td>
</tr>
<tr>
<td>H4</td>
<td>10</td>
<td>763</td>
<td>43</td>
<td>43</td>
<td>0.4</td>
</tr>
<tr>
<td>R3 V2</td>
<td>12</td>
<td>680</td>
<td>40</td>
<td>47</td>
<td>0.4</td>
</tr>
<tr>
<td>H2</td>
<td>15</td>
<td>642</td>
<td>32</td>
<td>49</td>
<td>0.4</td>
</tr>
<tr>
<td>R4 V4</td>
<td>20</td>
<td>786</td>
<td>35</td>
<td>49</td>
<td>0.4</td>
</tr>
<tr>
<td>H4</td>
<td>16</td>
<td>867</td>
<td>35</td>
<td>50</td>
<td>0.5</td>
</tr>
<tr>
<td>R5 V4</td>
<td>22</td>
<td>808</td>
<td>44</td>
<td>55</td>
<td>0.4</td>
</tr>
<tr>
<td>H4</td>
<td>16</td>
<td>763</td>
<td>46</td>
<td>50</td>
<td>0.4</td>
</tr>
<tr>
<td>R6 V2</td>
<td>27</td>
<td>872</td>
<td>56</td>
<td>56</td>
<td>0.4</td>
</tr>
<tr>
<td>H2</td>
<td>27</td>
<td>922</td>
<td>56</td>
<td>63</td>
<td>0.4</td>
</tr>
<tr>
<td>R7 V2</td>
<td>22</td>
<td>756</td>
<td>42</td>
<td>46</td>
<td>0.4</td>
</tr>
<tr>
<td>H2</td>
<td>17</td>
<td>671</td>
<td>54</td>
<td>47</td>
<td>0.4</td>
</tr>
</tbody>
</table>

Where H2 is wall two the right side and V2 is wall two the left side, H4 is the right side wall four and V4 is the left side wall four.

There was dissipation between walls and samples. For SDAS sample R5 and R7 are marked red because of few measuring points and sample R6 should be considered as an estimation.

Sample R1 had a significant amount of carbides. The other specimens were in the normal ranges (less than 1%).

The two samples with the most and least ferrite content was sample R2 respectively R6, with an average ferrite amount approximately 5 % and 1 %.

4.5 Sintercast parameters
The Sintercast parameters; modification index (MGM), inoculation index (MGI) and carbon equivalent (CE) has been obtained from the Sintercast process during casting (paragraph 2.6.3.1), see Table 14.

Table 14. Parameters measured by the Sintercast process.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Average CE</th>
<th>Average MGM</th>
<th>Average MGI</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1</td>
<td>57</td>
<td>32</td>
<td>46</td>
</tr>
<tr>
<td>R2</td>
<td>54</td>
<td>28</td>
<td>48</td>
</tr>
<tr>
<td>R3</td>
<td>56</td>
<td>26</td>
<td>56</td>
</tr>
<tr>
<td>R4</td>
<td>52</td>
<td>44</td>
<td>51</td>
</tr>
<tr>
<td>R5</td>
<td>50</td>
<td>44</td>
<td>55</td>
</tr>
<tr>
<td>R6</td>
<td>52</td>
<td>44</td>
<td>56</td>
</tr>
<tr>
<td>R7</td>
<td>54</td>
<td>39</td>
<td>59</td>
</tr>
</tbody>
</table>

4.6 Mechanical properties
The cylinder blocks are in accordance with CGI 400 (ISO16112/JV/400/S). For the standard tensile test positions the acceptable minimum according to the company specific requirements is 390 MPa and the usual maximum is about 450 MPa. In Table 15 the result for the tensile test specimens
corresponding to the thermocouple positions are shown, these results are from another report by Sebastian Edbom (Master thesis, royal institute of technology).

Table 15. Result mechanical properties TT-samples.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Tensile strength [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>TT 61C3</td>
<td>476</td>
</tr>
<tr>
<td>TT 61C4</td>
<td>453</td>
</tr>
<tr>
<td>TT 61C5</td>
<td>430</td>
</tr>
<tr>
<td>TT 61C6</td>
<td>523</td>
</tr>
<tr>
<td>TT 61C8</td>
<td>476</td>
</tr>
<tr>
<td>TT 61C9</td>
<td>476</td>
</tr>
<tr>
<td>TT 65C3</td>
<td>465</td>
</tr>
<tr>
<td>TT 65C4</td>
<td>450</td>
</tr>
<tr>
<td>TT 65C5</td>
<td>420</td>
</tr>
<tr>
<td>TT 65C6</td>
<td>519</td>
</tr>
<tr>
<td>TT 65C8</td>
<td>467</td>
</tr>
<tr>
<td>TT 65C9</td>
<td>456</td>
</tr>
</tbody>
</table>

All samples except position C5 have higher tensile strength than the usual maximum 450 MPa.

The tensile strength result for the reference samples (previous CGI castings) are shown in Table 16.

Table 16. Result mechanical properties for reference samples.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Tensile strength [MPa]</th>
<th>Average tensile strength [MPA]</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1</td>
<td>V2</td>
<td>424</td>
</tr>
<tr>
<td></td>
<td>H2</td>
<td>384</td>
</tr>
<tr>
<td>R2</td>
<td>V4</td>
<td>410</td>
</tr>
<tr>
<td></td>
<td>H4</td>
<td>404</td>
</tr>
<tr>
<td>R3</td>
<td>V2</td>
<td>415</td>
</tr>
<tr>
<td></td>
<td>H2</td>
<td>419</td>
</tr>
<tr>
<td>R4</td>
<td>V4</td>
<td>427</td>
</tr>
<tr>
<td></td>
<td>H4</td>
<td>424</td>
</tr>
<tr>
<td>R5</td>
<td>V4</td>
<td>453</td>
</tr>
<tr>
<td></td>
<td>H4</td>
<td>440</td>
</tr>
<tr>
<td>R6</td>
<td>V2</td>
<td>486</td>
</tr>
<tr>
<td></td>
<td>H2</td>
<td>460</td>
</tr>
<tr>
<td>R7</td>
<td>V2</td>
<td>422</td>
</tr>
<tr>
<td></td>
<td>H2</td>
<td>420</td>
</tr>
</tbody>
</table>
5 Discussion/Analysis
All calculations and measurements have been done by the same person. Since the measurements of the image analysis were done by hand a test with another person was made and the error margin was considered small.

5.1 Chemical composition
The chemical composition varies between the first and last cast cylinder block and also compared to the melt. These differences could depend on that the analysis was made at different laboratories and measuring errors. The magnesium fades with time according to [33].

5.2 Cooling curves and microstructure
The microstructure features; SDAS, ECS, nodularity and intercellular part will be evaluated against solidification time and also the pearlite lamellar distance and cooling rate will be plotted against each other. Because of unsuccessfully registered temperatures in the last cast block (65) only the result obtained, considering cooling curves, for the first cast block (61) will be analysed regarding microstructure.

5.2.1 Solidification time verses secondary dendrite arm spacing
In Figure 29 the solidification time vs. average SDAS for block 61 is shown.

Figure 29. Solidification time vs. average secondary dendrite arm spacing for block 61.

The relationship between SDAS and solidification time is as expected since the austenite grows until solidification. The longer the solidification time is the larger the SDAS will be, as said in paragraph 2.4. This relation has also been studied of M.M. Jabbari Behnam [24], and it is in good agreement with this result, since high cooling rate result in short solidification time.
5.2.2 Solidification time versus nodularity

Figure 30 show the irregular behaviour of the nodularity vs. solidification time.

For nodularity the irregular behaviour was expected, as said at page 4, the nodules could have been primary precipitated, formed at the eutectic solidification or from the last solidifying melt. The used image analysis cannot separate the nodules. The way to distinguish them is if a board of ferrite is present or not, if lack of ferrite the nodules has been formed in the last solidifying melt. Interesting positions are C9 and C4, they have almost the same geometry and the distance to nearest wall is the same, however they differ a lot in solidification time. The positions in the cylinder block may be the reasons for this difference.

5.2.3 Solidification time versus average eutectic cell size

The solidification time and average ECS is shown in Figure 31.

The eutectic cell size has a good correlation to the solidification time and since the ECS depend on SDAS, see paragraph 2.4, the behaviour is as expected as the SDAS had a good relation with the
solidification time. In the article by L, Elmquist et. al [50] the relation between ECS, SDAS and solidification time has been investigated and the results are the same. The thermocouples C4 and C8 are the ones that differ for the ECS. One possible reason for this deviation may be due to the positions in the cylinder block, thermocouple C4 is in a thick part and C8 in a thin part and is surrounded of sand which cools it down quicker.

5.2.4 Solidification time verses intercellular part
Figure 32 show the relation between the solidification time and intercellular part.

![Solidification time vs. intercell](image)

It has been suggested that the material between the cells, the intercellular volume controls the mechanical properties of grey cast iron [51]. The intercellular volume depends on the solidification route, for example solidification time as shown in Figure 32.

5.2.5 Cooling rate at 750°C verses pearlite lamellar distance
The connection between the calculated cooling rate at 750°C and the lamellar distance in the pearlite are evaluated. The lamellar distance should according to [37] get coarser if the cooling rate is low and finer if the cooling rate is high. However the lamellar distance stays the same even if the cooling rate varies, see Figure 33.
The lack of variation can be due to differences in how the lamellas are cut and because it is hard to measure the lamellas. Further on, the sand has a considerably lower thermal conductivity compared to the iron. The temperature of the casting may even out before the pearlite is formed. However, the thermocouples registered differences in cooling rate at 750 °C. The values are from about 1 K/min to almost 11 K/min. However there is still no visible change in lamellar distance which suggests that the pearlite formation is insensitive for this cooling rate. Also the time for solid state transformation ranges from approximately 10 min to 1h, see Table 10, possibly the time for solid state transformation has to be much longer or faster to see any difference in the lamellar distance for pearlite.

5.3 Microstructure for TC and TT
Comparing the microstructure of cylinder block 61TC and 65TC a clear difference can be seen. The nodularity amount is always more or equal while the ECS, intercellular part and SDAS are irregular with a hint of a trend. For the tensile test samples from block 61 and 65, there are instead clear contrasts. Block 65 compared to block 61 has lower nodularity, the ECS is either equal or higher and the intercellular part is lower. The liquid iron for block 65 is colder and the influence of both magnesium and inoculant has decreased. This means that the necessary undercooling for block 65 is larger since the inoculant has faded, however at the same time the iron is colder and also the amount of Mg is decreased. Considering this the nodularity should decrease as it does for tensile test samples. This is not the case when comparing 61TC and 65TC which may be explained by a cooling and/or nucleation effect from the thermocouples.

Figure 34 below shows the cooling curves for thermocouple C5 in block 61 and 65.

5.3.1 Microstructure for TT and wall distance
When evaluating the distance to nearest wall and the microstructure between 61TT and 65TT it seems like the thicker the wall is the less variation in nodularity but more variation in ECS. But no trend can be seen between the microstructure and nearest wall distance since there are more parameters to take into account.
5.3.2  Microstructure for TC versus TT
The difference in microstructure between 61TC and 61TT is probably due to the thermocouples which have had a cooling or nucleation effect or because the samples were taken from different walls and therefore the filling and flow could have had an effect.

5.3.3  Microstructure and tensile strength
For the nodularity and tensile strength no clear trend can be seen, however the position with the most nodularity also has the largest tensile strength. In the case of average ECS and tensile strength a good correlation can be distinguished, as seen before [3]. As said in paragraph 2.3 the eutectic cell size is believed to influence the mechanical properties in this way similar to the Hall-Petch relation. However further investigation was made where position C8 and C9 was compared with each other. This since they have the same tensile strength but the one microstructure feature that differs is AECS. Since the tensile strength is the same for as different AECS as $465 \mu$m and $594 \mu$m respectively, there is something else controlling the mechanical properties. When the different classes of graphite and the amount of each class was considered it was seen that position C8, with the smallest AECS, has more percentage of the larger graphite classes compared to position C9.

New investigations, for example [51], propose that the intercellular part can be of interest when deciding the mechanical properties. In this study there is some correlation between the intercellular part and tensile strength however the result of the intercellular part is not enough to say that it is the controlling feature.

Another possible reason to decide which microstructure feature that controls the mechanical properties is to think of the material as a composite, considering the metal matrix and the graphite precipitations alternatively the intercellular part and eutectic cells.

5.3.4  Microstructure and Sintercast
No relation could be distinguished between the microstructure of the reference samples and the Sintercast parameters. This was of interest because in this thesis only one ladle is cast.
6 Conclusions

- The microstructure depend on many parameters, one of them is the position.
- A clear relation between eutectic cell size and solidification time is seen.
- The secondary dendrite arm spacing increase with increased solidification time.
- The small variation in lamellar distance could depend on how the lamellas are cut, is also suggests that the pearlite formation is insensitive for the measured cooling rates, also possibly that the solid state transformation has to be longer or faster.
- The thermocouples have contributed with a cooling and/or nucleation effect.
- The variation between the tensile test samples in block 61 and 65 probably depend on variation in temperature and chemical composition.
- It is not only one microstructure feature that controls the mechanical properties.

7 Further work

- A deeper image analysis to distinguish which type of nodules and also further study of the intercellular part.
- Continue to evaluate the microstructure and the parameters that influence it.
- Pore analyses
- Other methods for microstructure analysis, for example SEM, deep-etch, tomography
8 Acknowledgement
I would like to express my gratitude to:

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Sebastian Edbom for the cooperation throughout the experiment.

Scania foundry, with employees, for giving me the opportunity and their work effort during the experiment.
9 References


[20] Scania in-house learning material


[40] Scania in-house report by Jessica Elfsberg


[42] Interview with John Moré Process engineer at Scania


