OPTIMIZATION OF THE CHEMICAL ANALYSIS OF SS-EN-GJL-250 USING CASTING SIMULATION SOFTWARE

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Product Development and Materials Engineering
This thesis work has been carried out at the School of Engineering in Jönköping in the subject area of materials engineering. The work is a part of the Master of Science programme. The author takes full responsibility for opinions, conclusions and findings presented.

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Abstract

The main purpose of the thesis work is based on achieving same mechanical properties on the three different sized bearing housings. The key mechanical property that had to be focused on was the hardness of the parts.

In order to achieve this goal, chemical compositions of the parts have studied. However there were some limitations on the composition variants. Allowed variables of the compositions are silicon, nickel and copper. Due to necessity another element, Molybdenum (Mo), was also introduced. After many simulations three different compositions are proposed. Then the feasibility of results of casting simulation software investigated. And finally an optimization guideline has proposed.

Chemical composition researches have carried on casting simulation software, which is called Magma®. Following the completion of the simulations phase, proposed compositions trial casted at the company. Subsequent to trial castings cast parts had tested for their hardness values. In order to bring the thesis to completion simulation outputs and trial test results had compared.

With the help of a casting simulation software composition optimisation of different sized parts could be easily optimised in order to achieve same results.

Many simulations are executed with different composition for the silicon, nickel, copper and molybdenum variants. It was seen that Mo additions significantly increase the mechanical properties of the parts. Nickel and copper acts similarly on the hardness values, however nickel addition reduce undercooling tendency at a greater rate.

Good inoculation is vital for the parts with thin sections. Decent inoculation helps to improve the microstructure and helps to get closer results to the simulated values. However software represents key information about undercooled zones on the part.

Software ensures 95% to 97% correct values on hardness results.
Keywords

Grey Cast Iron
Alloying Elements
Hardness
Tensile Strength

Silicon
Copper
Nickel
Molybdenum
Inoculation
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The engineering department of SKF Mekan AB encountered a problem of trusting the outcomes that are generated with casting simulation software. Their objective is to find whether it is possible to quite easily optimize an analysis with casting simulation software, so the Engineering and Pattern Departments could use the outcomes for casting the parts, without making any further tests or analyses. In this thesis work, the company given CAD models are simulated on the Magmasoft, and the requested mechanical values are achieved by arranging the suitable chemical composition. Later on, the envisaged chemical composition is trial-casted in the company and subsequent mechanical tests are executed in the laboratory.

1.1 Background

Casting process is used by many companies due to its ease of production, freedom of design modification and material choice. Casting is a fast process from starting material to the final product. Because of these simplicities many researches and extensive work had been done in order to find complete understanding of this process. Huge amount of researches and knowledge of the effects of variants on casting and solidification processes resulted in the development of the simulation softwares. [1]

Nowadays many foundries are using softwares in order make more controllable products during the casting process. With the help of the simulation softwares, designers and foundry men have the chance of testing improvement options and affectivity of variants. Instead of making time consuming and expensive trial castings, simulations could be executed in order to find the results. In that manner potential problems could be found and eliminated already in the design phase. Also many variants of the products could be optimized without the need of the trials. [1]

Through all these benefits of the software, engineering department of SKF Mekan encountered the problem of realisation of the simulation results. Working with many different parts, patterns and models, seeing the effects of variants is vital for the department. However it would become very expensive and time consuming for making trial castings for each modification. On the conclusion they would like to search the possibility for the ease of chemical analysis optimisation and its reliability for reaching similar results for different products.

1.2 Purpose and research questions

The main purpose of the thesis work is based on achieving same mechanical properties on the three different sized bearing housings. The key mechanical property that is going to be focused on is the hardness of the parts. However the envisaged chemical composition must fulfil the tensile stress values of EN-GJL-250 specification also. The research questions could be defined as:
Introduction

- How should the chemical composition of the parts be arranged so that each part will have same mechanical properties?
- Is it possible to optimize an analysis in casting simulation software such that the results could be trustworthy for direct use?
- In order to optimize the chemical composition of a certain product how should be the guidelines created?

1.3 Delimitations

In order to find a suitable alloying composition main interest is given on the effects of silicon, nickel and copper, as it is requested by the company. Also in order to achieve the goal, introduction of another element (Molybdenum) became necessitated.

In this work filling or filling related simulations of the parts are not investigated deeply as the matrix or graphite structure is mostly affected by cooling ratio, chemical composition and the hot spots. However in order to obtain good and feasible results, simulations are executed with the filling simulations.

Most efficient way to eliminate hot spots or heat affected zones is a design change but it won't be investigated due to the limitations of the thesis proposal. Also by the request of the SKF Mekan AB, runner and gating systems of the moulds are not shown in the figures of this thesis work.

Beside those, main study of thesis work focused on achieving demanded hardness values. Yet the tensile strength values are also mentioned. Hardness values are measured from surface of the parts and tensile strength values are measured from separately casted test samples.

1.4 Outline

Firstly theoretical background of relation between the hardness and composition of grey cast iron will be introduced. Then metallurgy of the grey cast iron and alloying elements will be explained. Subsequently the inoculation will be explained and the theoretical background will be finished.

On the method section casting simulation software will be introduced briefly, Brinell hardness test will be explained and CAD models of the parts and initial values of the simulations are going to be presented.

Furthermore results of the simulations and proposed compositions for the trial castings will be described. Then the findings of trial castings are going to be exposed.

Finally the results will be analysed and discussed and the report is going to be concluded.
2 Theoretical background

The term “cast iron” is used for identifying an alloying system which consist of major elements (iron, carbon, silicon), minor alloying elements (i.e. manganese, copper, magnesium, etc.) and the trace elements. Solidification of the cast iron is mostly depending on the alloy composition. Subject to alloying composition cast iron could solidify in either thermodynamically metastable iron-iron carbide (Fe₃C, named as cementite) or stable iron-graphite system. These two basic system types show greater differences in their mechanical properties, because the mechanical properties are mainly derived from the matrix structure. “The metallic matrix is tough and gives the cast iron its strength, while the graphite particles are brittle and lower the strength properties. (Diószegi, A., 2004, p1)” [2-4]

The matrix structure and graphite shape effects the material properties. As a result of this, classification of cast iron could be made according to these features: [2,4]

- According to the graphite shape:
  - Lamellar (flake) graphite (FG);
  - Spheroidal (nodular) graphite (SG);
  - Compacted (vermicular) graphite (CG);
  - Temper graphite (TG);
- According to the matrix:
  - Ferritic: Soft with relatively low strength;
  - Pearlitic: Hard and mechanical properties could be changed with cooling rate;
  - Bainitic: Usually formed by austempering that results in high tensile stress, toughness and fatigue resistance;
  - Austenitic: Retained when high alloying content cools. Good heat and corrosion resistance;
  - Martensitic: Hard but brittle;
- Common basic classification:
  - White iron: Matrix structure has white appearance. The carbon precipitates as cementite in relatively large particles. That increases the bulk hardness of the part. Contrary have low toughness;
  - Grey iron: Matrix structure has grey appearance. Carbon precipitates as graphite which gives better tensile strength values. Also it has higher compressive strength values comparable to steel;
  - Ductile iron: As a result of magnesium or cerium addition the graphite precipitates in nodular form. Have a reasonable ductility;
Malleable iron: Cast as white iron and then heat treated for better mechanical properties.

Beside those classifications some irons with specific forms also exist and have special names. [2]

In 1997 a European Standard EN 1561:1997 was approved [4]. According to this standard EN-GJL-250, refers to grey cast iron with 250N/mm² minimum tensile strength measured on the test piece. Table-1 shows information regarding the similarities in the national standards (Note that the values given below are not necessarily identical). In the SKF Mekan AB this specification is called as V10 and the required specifications of hardness and tensile strength are 180-230 HB and 250-350 N/mm² respectively. (Appendix I)

Table 1 National Standards. Source: Ref 4 p31.

<table>
<thead>
<tr>
<th>Country</th>
<th>Specification</th>
<th>Designation</th>
<th>Minimum tensile strength (N/mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Europe</td>
<td>EN 1561:1997</td>
<td>EN-GJL</td>
<td>100 150 200 250 300 350 400</td>
</tr>
<tr>
<td>Japan</td>
<td>JIS G5501 1995</td>
<td>FC</td>
<td>Class</td>
</tr>
<tr>
<td>Russia</td>
<td>GOST 1412 1979</td>
<td>Sch</td>
<td>10 15 20 25 30 35 40 50</td>
</tr>
<tr>
<td>USA</td>
<td>ASTM A48-94a</td>
<td>Grade</td>
<td>6.5 9.7 12.9 16.2 22.5 27.5 32.5</td>
</tr>
<tr>
<td></td>
<td>ASTM A48M-94</td>
<td>Grade</td>
<td>100 150 175 225 275 300 350</td>
</tr>
<tr>
<td>International</td>
<td>ISO 185-1988</td>
<td>Grade</td>
<td>6.5 9.7 12.9 16.2 22.5 27.5 32.5</td>
</tr>
<tr>
<td></td>
<td>Equivalent tonf/in²</td>
<td></td>
<td>6.5 9.7 12.9 16.2 22.7 350 400</td>
</tr>
</tbody>
</table>
2.1 Relationship between composition and strength of grey cast iron

By the means of varying chemical compositions the size, amount and the distribution of the graphite flakes could be altered according to the required microstructure or mechanical properties. The major elements in cast irons are iron, carbon and silicon. As a result cast irons could generally be thought of iron-carbon-silicon ternary alloys [2,4]. A section from the equilibrium phase diagram at 2.5% Si can be seen in Figure 1. As it seen on the diagram, eutectic point of the composition moved from 4.3% C (eutectic composition of regular Fe-C phase diagram) to 3.5% C.

![Iron-carbon phase diagram at 2.5% Si](image)

"The addition of silicon to binary Iron-Carbon alloy decreases the stability of iron-carbide and increases the stability of ferrite (the α field is enlarged, and the γ is constricted)." (Davis, J.R., 1996 p5) As the amount of silicon content in this tertiary system increases, amount of carbon content in the eutectic decreases [2,4].

An index was introduced, in order to define a relationship between carbon and silicon amount for their combined effect on the alloy system, which is named as “Carbon Equivalent (CE)”. Binary system of Fe-C alloy has an eutectic at 4.3%
C content. When the alloying elements are introduced amount of carbon in eutectic is decreased [2-4]. We can define that with an equation [2]:

\[
\%C + \frac{1}{3}\%Si = 4,3 \quad \text{(Eq. 1)}
\]

According to that we could simply define CE as how close is a given composition to its eutectic composition. We could simply define CE with following equation [2]:

\[
CE = \%C + \frac{1}{3}\%Si \quad \text{(Eq. 2)}
\]

In addition some alloying elements are also altering the amount of carbon in eutectic composition. However phosphorous have unignorable effects if it is used in large amounts. Phosphorous have a limited solubility in the austenite and it tends to decrease with the increasing amounts carbon. As a result during the solidification it segregates into the melt [2,5]. In order to make a more rational calculation on CE following formula should be introduced [2,4]:

\[
CE= \%C + (\%Si + \%P)/3 \quad \text{(Eq. 3)}
\]

CE ratio of a cast iron could be useful to have an approximate value of expected strength in a section, as the composition of matrix and graphite flakes are related to alloy composition. Although different alloys with same CE may have different properties, since the same CE ratio can be obtained with different compositions. [2,4]

The strength of cast iron is adversely related to increasing ratio of CE. While the increasing amount of carbon and silicon promotes the graphitization ratio and decrease the tendency of chilling, the strength will be decreased because of the promotion of ferrite and coarsening of the pearlite lamellas. Figure 2 shows the relation between tensile strength and CE. [2]

![Figure 2](image)

Figure 2 General influence of carbon equivalent on the tensile strength of grey cast iron. Source: Ref. 2 p9
2.2 Grey iron metallurgy

As it mentioned before properties of grey cast iron are affected by the graphite shape. Another factor that also has an influence is the distribution of graphite flakes. In order to make a standardization for graphite shape and distribution, American Society for the Testing of Metals (ASTM) proposed a system for identification. ASTM specification A247 classifies the form, distribution and size of the graphite [2,4]. According to the ASTM A247 graphite forms for cast irons are shown in Figure 3.

![Graphite Forms Diagram](image1)

**Figure 3** Standard graphite forms in cast irons according to the ASTM A247. Source: Ref 6

In grey cast irons carbon is precipitated in Type I graphite forms. ASTM A247 also defines the graphite distributions. Figure 4 shows these distributions.

![Graphite Distributions Diagram](image2)
By the means of different graphite formations, resulting parts also show different properties. Properties of these formations are described below [2,4]:

- **Type A**: Graphite flakes are distributed randomly and they have uniform flake size. This type of graphite structure forms when there is a high degree of nucleation in the liquid melt, because the solidification occurs close to equilibrium graphite eutectic. In other word, melt is solidified with minimum amount of undercooling. Thus causing to have high amount of pearlitic structure. Type A formation gives optimum mechanical results and preferred for engineering applications. Due to its higher pearlite content it will have uniform mechanical properties all along the part and will give better surface finish.

- **Type B**: In melts with near eutectic composition if the melt solidified at higher undercooling rates than those occur at Type A, graphites are distributed in rosette pattern. During the solidification phase nucleation occurs at low levels and causes the eutectic cell to grow. At the centre of the rosette finer flakes formed due to undercooling, but as the structure grows flakes became coarser and shows Type A distribution.
Theoretical background

- **Type C**: This type of graphite distribution occurs at hyper-eutectic compositions which have high carbon content. First precipitating graphites formed this Kish graphite, which appears as straight, coarse plates. Kish graphites significantly reduce mechanical properties and cause rough finish surfaces after machining operations. Due to its higher amount of graphites, parts have high degree of heat transfer ratios.

- **Type D and E**: These graphite types are formed when the undercooling ratio is high but still not sufficient to create carbide formations. In other word they are formed because of insufficient graphite nucleation. Both types have fine undercooled graphites. Type D flakes are randomly orientated while Type E have preferable orientation. Fine flakes in both types could increase the iron matrix hardness. However this type of morphologies are not desired for engineering applications, because they are preventing fully pearlitic formations. Moreover as the ferrite have lower tensile strength than pearlite resulting tensile strength of the part would be reduced.

Without going into detailed information, basically it could be said that liquid melt of cast iron is a suspension of carbon, which is dispersed as various sizes of graphite particles. During the solidification each of these graphite particles are theoretically expected to become crystallization centres and form single eutectic cells. Then these cells continue to grow and forms the graphite structure of the part. [2,6,7]

In grey (Lamellar / Flake graphite) cast iron eutectic cells develop more or less spherical shape. Formation phases of the eutectic cell is shown in Figure 5. Each of these cells consist of interconnected graphite flakes and austenite. Later on the solidification, randomly distributed eutectic cells initiate the precipitation of graphite and austenite. This process is called nucleation. During the precipitation graphite lamellae start growing from the nucleation centre and keep the contact with the melt. The spaces between the lamellae are filled by the austenite. [2,6,7]

Sum of all a relation between the eutectic cell count and mechanical properties could be established. For example, the strength of the cast iron would be improved by increasing the amount of eutectic cells. Because higher amount of eutectic cells will precipitate more ferrite and increase the amount of Type A graphites. Also the tendency for chill would be decreased with the higher count graphite flakes. On the conclusion, it can be said that anticipated mechanical properties could be altered by modifying the cell counts. [7]
Theoretical background

Figure 5  Schematic description of development of the eutectic cell and SEM picture of the eutectic cell. Source: Ref 7

In order to define an adequate composition, effects of the alloying elements should be considered. In most of the cases alloying elements are used for promoting the pearlite formation. Having higher pearlite content leads to have higher strength values in the part. In this section effects of the elements will be explained briefly. Nevertheless effects of silicon, nickel, copper and molybdenum will be explained further on the next section, as they are the domain of the thesis.

Carbon (C) is one of the major element of cast irons. By having highest addition to CE, it strongly influences the strength and hardness of the cast iron. Also C have an effect on the castability of the part, because of the liquid shrinkage and feeding ability [4]. Correspondingly increasing CE causes thermal conductivity to increase. [9]

Silicon (Si) is the other element of the ternary alloy system, which is already mentioned in section 2.1. It is a strong graphitizing element and decreases the tendency of chilling. Mostly used around 2%. [2,4,10]

Phosphorous (P) is a minor alloying element with two other interacting elements, manganese and sulphur. Control of these elements has crucial importance on the product consistency. Although it is not added intentionally, in the general case P increases the fluidity of the molten metal. Source of the P is scrap metals or pig irons, those added into the melt. It creates a phosphide phase on last solidifying zones of cast irons, thus reduces the shock resistance of part. Additions of higher content could promote shrinkage porosity. P maybe used for thin section and low strength castings, in order to improve castability by the means of increasing fluidity. Should be kept below 0,1% in order to avoid phosphide phase. [2,4,5]

Sulphur (S) is a harmful element for grey cast irons and should be kept as low as possible. Its effects are omitted with the addition of the manganese and mostly removed as a slag. However if the slag remained under the casting skin, could cause blowhole defects. Contrary it strongly effects the nucleation of the graphite. It is best to keep S content below 0,12%. [2,4] The reason of this content and nucleation effect of the sulphur is further explained in Section 2.4.
Theoretical background

Manganese (Mn) is used for neutralizing the effect of S in the cast irons. Mn forms manganese sulphide (MnS) with S. During the cooling phase MnS float out of the metal into the slag layer. Required amount of Mn to neutralize the effect of S could be calculated with the equation 4. Also Mn would increase the strength of the cast by stabilizing the pearlite. However excess use of Mn, can affect the nucleation inversely. Mostly used 0,5% - 0,8%. [2,4,10,11]

\[
\%\text{Mn} \geq 1,7 \times \%\text{S} + 0,3\% \tag{Eq. 4}
\]

Chromium (Cr) increases the hardness and strength of grey iron, by suppressing the formation of free ferrite. In this manner Cr promotes the formation of pearlitic structure. On the other hand Cr also endorses carbides and could cause chill formation at the edges of casting when there are thin sections or high Cr addition rates. Generally used up to 0,5%. [2,4]

Molybdenum (Mo) additions of 0,25% to 0,75% have a great influence on the strength and hardness of the grey iron. Mo strengthens the matrix structure and refines the graphite flakes. Also stabilizes the structure at high temperatures. If the Mo extent goes beyond the 0,95%, it could promote molybdenum carbides. [2,4,10,11]

Copper (Cu) also increase the strength and hardness by promoting the pearlitic structure. This action is implemented by reducing the free ferrite. Due to its mild graphitizing effect, reduces the risk of chill in thin sections. Must be added in high purity in order to avoid tramp materials. Mostly used up to 0,5%. [2,4,10,11]

Nickel (Ni) does not have big effect on tensile strength of grey cast iron and does not promote carbides. Ni have minor graphitizing effect. [2,10]

Tin (Sn) is a strong pearlite stabilizer however only small amounts are effective. Addition in higher amounts would increase embrittlement. Used up to 0,1%. It may arise from addition of steel scraps. [2,4]

Lead (Pb) is a harmful element on the structure of flake graphite. Even in very small inclusions, such as 0,004%, could cause serious loss in the tensile strength. Might arise from steel scraps or copper alloys. [2,4]

Aluminium (Al) is promoting hydrogen pinhole defects. This phenomena is performed by increasing the tendency for hydrogen pick-up from the sand moulds. It could arise from the automotive steel scraps. [2,4]

Nitrogen (N) above 0,01% causes blowhole or fissure defects. However compacts graphite and promotes pearlite, consequently increases the strength. Existence of N could arise from the high steel charges. These steel charges are used during the cupola melting (Cupola furnace have a big cylindrical shape and positioned vertically. It is used for melting raw materials and prepare the casting melt). N can be treated with the addition of the Al or titanium (Ti). [2,4]
2.3 Effects of silicon, nickel, copper and molybdenum on grey iron properties

As it is mentioned above silicon is a strong graphitizer and reduces risk of chilling. Conversely its effect on the ultimate tensile stress (UTS) is not changing linear with the added amount. Bates, C.E. [10] made a research with the varying amounts of Si content from 1,59% to 2,42%. Findings show that additions of up to 2% Si decreased UTS, because it caused more graphite to precipitate. Nonetheless, additions of 2% to 2,4% caused UTS to slightly increase. Plausible reason on this case could be a substitutional strengthening of matrix which is caused by the addition of Si. Higher Si additions have hardening and strengthening effect on the matrix structure, at the same time produces longer flakes those lowering the UTS.

In literature there are many researches regarding the effect of nickel on grey iron properties [10,12-14]. Researches are made for investigating the effects of Ni either alone or with other elements. One of the main result of all is that Ni promotes fine pearlite but decrease strength. In a research [10] tests are made with varying amounts of Ni from 0,06% up to 1,62%. According to the research with the increasing amounts of Ni chill depth of the cast sample decreased and bulk hardness increased. However on the additions of over 0,64% matrix hardness did not changed. Although the higher additions of Ni strengthened the matrix, the graphitizing effect of the element leads to larger flakes, which decreased the effect on the matrix strength.

Another researcher [13] vary amount of Ni with the introduction of cerium inoculation in order to develop a cheaper composition for an existing product. According to research crack propagation length reduced, thermal fatigue developed, graphite dispersed in refined grains and the number of the graphite count in a microstructure improved. Although the cerium inoculation improves the effect of Ni on graphite count, they act independently.

In the event of copper addition, researchers [10-12,15-17] explained that Cu promote finer pearlite and that way increase the stability of pearlitic structure. In his research Bates, C. E. [10] varied the amount of copper from 0,06% till 0,85%. Conferring to his findings Cu addition increase strength up to 0,35%. However the effect on higher amount of additions is much less and higher Cu additions have graphitizing effect. When the amount of Cu is increased, density, bulk and matrix hardness slightly increased. Contrary graphite surface area slightly decreased with the elongation of flake length.

According to researches [10,11,16] molybdenum have a thriving effect on the strength of cast iron. Researchers made tests with varying amounts of Mo addition in order to find its effect on strength and microstructure. Bates, C.E. [10] showed that increasing amount of Mo, raises bulk and matrix hardness, slightly reduce C volume fraction and tends to refine maximum graphite flake length. Xu, W. et.al. [11] and Hayrynen, K.L. et.al. [116] worked on grey iron in order to reach ausferritic structure (acicular grey iron with bainitic matrix) [17] without the need
Theoretical background

of austempering the grey iron. In austempering process solidified part is reheated up to a specific temperature and kept at that temperature for certain amount of time (tempering). During tempering process ferritic or pearlitic matrix of the part is transformed into ausferritic structure. This structure consists of 60-80 % bainitic ferrite and retained austenite. Due to the reheating process carbides are eliminated. Both researches showed that Mo and Cu worked in synergism and amount of at least 0,5% Mo is necessary to modify the matrix microstructure without changing the graphite morphology. In addition to those effects Mo addition increases the modulus of elasticity [18].

2.4 Effect of inoculation

Inoculation could be defined as late addition of small quantities of alloy mixture into the molten iron in order to affect eutectic cell size and graphite distribution [19-21]. By the means of altering graphite size, shape or distribution, mechanical properties and machinability of the cast can be changed. Although the alloying elements might have same inoculation effects, alloying and inoculation should not be confused. The effects of the inoculants depend on the inoculant composition and amount used, temperature and time used for addition. [2,4,19]

Inoculation could be added into ladle or after the melt left the ladle (called Late inoculation). In late inoculation, it can be added either while entering the mould (in-stream inoculation) or in the mould with the help of an insert (in-mould inoculation). As they have a short effectiveness time they should be added as late as possible. [2,4,19,20]

Materials those used as inoculant lose their affectivity after 10 to 20 minutes, this occurring called fading. Inoculants have highest efficiency just after the addition. The rate of fading depends on the composition of the inoculant and the condition of the melt iron. It should be emphasized that inoculants are intentionally arranged to have fading. Further on from a certain point, higher amount of nucleation sites would lead to non-uniform graphite distribution. [2,18]

By means of inoculant many elements or alloys are used [2,20,21]. Silicon based alloys are most common used ones [2,4,19-22]. Beside those rare earth metals [23,24] and misch metals [25] are also used. Additionally some inclusions could act like nucleation site [26].

Edalati, K. et.al. [22] worked on effects of silicon carbide (SiC) and ferrosilicon (FeSi) with different pouring temperatures. It appeared that SiC addition lead to achieve finer microstructure because of higher liquidus and eutectic temperature, increased fluidity and decreased chill depth. Also increasing pouring temperature leads to increased liquidus temperature and decreased eutectic temperature.
Da, S. et.al. [23] researched the effects of rare earth (RE) metals inoculation to grey cast iron. It showed that proper amount of RE addition decreased eutectic cell size and purified the molten iron (reduced oxygen and sulphur content). In addition, when added in small amounts decreased the chill tendency though the higher amounts have opposite effect. Beside those effects the quality of grey iron could be significantly altered with RE inoculation, as a result of existence of RE in both graphite and matrix. Fengzhang, R. et.al. [24] worked on the effects of FeSi75+RE and FeSi75+Sr inoculation. During the experiments varying amounts of RE and strontium (Sr) had been investigated. It appeared that RE inoculation caused to have higher strength, hardness and better matrix homogeneity.

Vadiraj, A. et.al. [25] made experiments with misch metal inoculations. According to the research misch metal inoculations could affect the graphite morphology and matrix structure depending on the alloying elements of misch metals.

Sulphur content of the cast irons are generally kept under certain content. In most cases free S is controlled with Mn addition. However as a free element it has very strong effect on nucleation. Because it forms iron carbides (FeS) on solidification phase and prevents graphite cell growth and cause serious chilling. Effect of S content is shown in Figure 6. As it seen from the figure S has lowest effect on microstructure between 0,05 to 0,12% contents. As a result it is advised to keep S levels below 0,12%. However due to undercooling effect S content strongly affects cell counts. [2,27]

![Figure 6](image)

**Figure 6** Effect of sulphur on chilling tendency of cast irons. Source Ref:2
Riposan, I. et.al. [26] introduced a new approach for possible nucleation sites during the solidification phase. In regular inoculation processes extra materials are added to the melt in order to increase the nucleation. However according to their research micro-inclusions of the cast parts are also acting as possible graphite nucleation sites. Especially Mn(X)S compounds are acting as major nucleation sites. In castings small oxide particles act as possible nucleation site for Mn(X)S. Later on these bigger particles start to act as further nucleation site of graphite flakes even with low undercooling levels.

2.5 Effect of pouring temperature

Increased pouring temperature could result in higher risk of gas entrapment, inclusions, poor metal structure, shrinkage, interrupted metal walls, mould penetration. Due to higher temperature the liquid melt will interact with air or mould surface for a longer time. During these interactions higher amount of air is taken into the melt. Later on the solidification phase this entrapped gases could lead to porosity or other problems. On the other hand the sand could start to corrode from surface, burn or release vapour or other gases because of the longer interaction time. This longer interaction could cause other forenamed problems. [2]

On the other hand lower pouring temperatures would lead to partially filled cavities, misruns, blow-holes and chill. Main cause of this case is lower fluidity or already solidified melt. [2]

According to the Edalati, K. et.al. [22] higher pouring temperatures resulted in lower amount of Type A graphite formation, increased chill depth and decreased eutectic cell count. Higher pouring temperatures resulted in to have higher liquidus temperature and lower eutectic temperature. Increasing difference between these temperatures resulted in higher undercooling ratios. Due to the undercooling higher quantity of graphite lamellae are formed other than Type A distribution.

2.6 Previous studies

In order to find a suitable base for arranging the outline of the thesis study, many sources are investigated during the literature study. Although there are many studies [3,28-31] which are carried on with the help of casting simulation softwares, none of them are focused on chemical composition optimization. However there are some existing researches which a relation could be specified. Especially research of Kumruoğlu, L.C. [30] could be easily optimized for this thesis work. Research is focuses on evaluation of the mechanical and microstructure properties of a chilled cast iron part.

On the other hand there are some researches [10,11,13,32] that are focused on composition optimisation by the means of trial castings. Even so the amounts of the researches that were studied on chemical optimization of grey cast irons are less than other casting types.
Despite the few amount of researches some are closely related to thesis work. For example in their research Xu, W., et.al. [11] used ASTM Class 35 alloy composition as a base starting point for further investigations. On the end of their research they proposed a feasible composition with good mechanical properties. As it could be seen from Table 1 also, Class 35 and GJL-250 are the same standards.

Combining the works of Kumruoğlu, L.C. and Xu, W., et.al. became helpful for the understanding and development of thesis work.
3 Method and implementation

In this thesis work whole study is aimed at finding a suitable chemical composition in order to realize the technical specifications. Chemical composition researches are carried on casting simulation software, which is called Magma\textsuperscript{5}. In the end final results of the compositions are trial casted at the company. The cast parts are then tested for their hardness's.

3.1 Magma\textsuperscript{5}

Magma\textsuperscript{5} is software package, developed by Magma GMBH. It is used for simulating the filling and solidification processes of casting. With the aim of reaching these goals the software uses finite differences method. In this method whole part is divided in finite elements, and the numerical analyses are carried on for each finite element in order. [1]

Magma\textsuperscript{5} software package consist of many modules and this study is carried on MAGMAiron module. The MAGMAiron module was developed for the solidification and feeding simulation of the grey, ductile and compacted graphite irons. The exact composition of the melt is used for calculating the nucleation, liquid fraction and solidification behaviour with empirical relations [3]. In this way user is provided with quantitative information about the solidification morphology of cast iron alloys as well as the distribution of the mechanical properties after solidification. [1]

3.2 Brinell hardness test

The hardness's of the parts are measured by Brinell test. In test procedure a hardened steel ball with 10mm diameter is pressed into the surface with a load of 3000 kgf. For different materials applied force, diameter and material of the ball is arranged according to the tested part. For softer materials applied force is reduced, on the other hand for harder materials steel ball is replaced with tungsten carbide ball. When the load is removed after a specified amount of time, damaged area is measured. An illustration is shown in Figure 7. According to the involved area, surface hardness of the part could be calculated with equation 5. [33]

\[ HB = \frac{2P}{\pi D(D-\sqrt{(D^2-d^2)})} \]  
(Eq.5)

P= Applied force (kgf)
D= Diameter of the ball
d= Diameter of the damaged area
Method and implementation

3.3 Trial castings

The trial castings are carried out at SKF Mekan AB. During the trials 3 different alloy composition have been prepared. Alloy 1 and 2 are used for casting SNL-511 and SNL-517 and alloy 3 is used for casting SNLN-3056.

In order to arrange proposed alloy compositions a base melt is prepared in the induction furnace. Base melt is then poured into the pots in order to arrange suitable alloy compositions. During the trial castings, pots of 500 Kg capacity are used. Once the base melt is poured to the pots, slag layer is removed from the surface of the melt. After that alloying elements with calculated amounts are added into the pots. Then the base melt is stirred for decent mixture of alloy composition.

Before pouring the prepared alloyed melt into the sand moulds, some of the melt is poured into the test moulds. During the trials three different test moulds (Figure 8) are used: A: Composition test specimen; B: Chill test specimen; C: Tensile test specimen. The acquired specimens are then used for testing the chemical composition, carbide formation tendency and tensile strength.
SNL-511 and SNL-517 are manufactured in the automated production line (further explained in section 3.3.1.1), which is used for mass preparation of sand moulds, and casted from the same alloys. Before preparing the sand moulds, the patterns are marked with “1” and “2” and “HB” in order to define the trial casted parts regarding their alloy compositions (Figure 9,10).

Figure 8  Test specimen moulds.

Figure 9  SNL-511 pattern, marked for trial alloy 1.
SNLN-3056 is manufactured in horizontal casting production line because of its big size (Figure 11,12).

Figure 10  SNL-517 pattern, marked for trial alloy 2.

Figure 11  SNLN-3056 pattern.
3.3.1 Pouring process

Once the alloyed pots are placed for pouring process, inoculant is added into pots. Company is using Foundrysil from Elkem [35] as a ladle inoculant. The trial castings are carried out on a busy continuing production line with breaks for the trials. Therefore some compromises are given during the trial castings. These compromises are:

- The casting temperature of the molten alloys didn’t check during the pouring procedure. On the regular castings before the pouring process, final alloyed melt is given special preparation (i.e. further heating, melt treatment, etc.). However this preparation requires decent amount of time and further heating. On the other hand trial pots are rather small in size and require less preparation. In order to prevent the cooling of the pots they are poured without checking the melt temperature and making the preparation.

- Ladle inoculation is used instead of in-stream inoculation.

After the parts are solidified they are removed from sand mould and delivered to sand-blasting machines.
3.3.1.1 Automated production line

DISAMATIC is an automatic production line used for mass preparation of flaskless sand moulds. It basically consists of mould preparation unit and mould conveyor. This system developed by Danish Technical University professor Vagn Aage Jeppesen in the late 50’s. [36,37] A diagram and picture of this line can be seen on Figure 13 and 14.

![DISAMATIC sand moulding principle](image)

Figure 13 DISAMATIC sand moulding principle. Source: Ref 38

![Mould filling process](image)

Figure 14 Mould filling process. Source: Ref 39

3.4 CAD models

The cad models of the project parts are given by the company (Annotation: Runner systems are not shown in the figures of the thesis). The parts are used for ensuring housing for bearings. Three different sized models are chosen for analysing the suitable chemical composition, because hardness of the part is subjected to the cooling rate during solidification [40]. Cooling rate is directly affected by composition, inoculation, mould type and part size. [2] Figure 15 shows placement of the bearing and its respective parts onto housings. In Figure 16 the size comparison of the parts could be seen.
Figure 15  Picture and exploded view of a bearing housing system. Source: Ref 41

Figure 16  Size comparison of the parts, which are used for the simulations.

3.4.1  Small sized casting

FB-SNL 511-609: Small sized casting with rather thin sections. Filled in vertical position with four casting parts. Placement of the parts can be seen in Figure 17.
3.4.2 Medium sized casting

FB-SNL 517: Rather bigger size and slower cooling rates than the small. Horizontal filling and two casting parts. Can be seen in Figure 18.

3.4.3 Large sized casting

FB-SNLN 3056: Being large sized casting, cause to have slow cooling rates. The casting is fitted with filters. Casting is shown in the Figure 19.
3.4.4 Simulation values

All of the moulds are filled in manner of gravity filling [42]. Pouring rate of the melt is defined by time. Because in the real case the pouring process is started with smaller rates, increased to a specified rate and end by decreasing the rate. Time specified setting suits more to the real case.

- Mesh size: ~20 million mesh cells
  - SNL-511: ~1,6 million metal cells
  - SNL-517: ~1,9 million metal cells
  - SNLN-3056: ~1,5 million metal cells

- Heat Transfer Coefficient: Temperature dependant HTC

- Sand: Green sand

- All pouring temperatures are selected at 1400°C at the beginning as it is the default setting of Magma. However later on the pouring temperatures are adjusted to their real case values.

3.4.4.1 FB-SNL 511-609

- Pouring time: 12s
- Pouring temperature: 1360-1390°C; selected value: 1375°C
3.4.4.2 **FB-SNL 517**
- Pouring time: 12s
- Pouring temperature: 1350-1380°C; selected value: 1365°C

3.4.4.3 **FB-SNLN 3056**
- Pouring time: 20s
- Pouring temperature: 1350-1380°C; selected value: 1365°C

3.4.4.4 **Chemical Composition**

The basic composition of the castings could be given as follow. All percentages are weight ratios of system. “$w, x, y, z$” are variables of the composition. Other composition values are selected from the SKF Mekan AB’s requirement specifications (Appendix I). Base composition is shown in Table 2.

<table>
<thead>
<tr>
<th>Table 2</th>
<th>Base composition and variables for the research.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>C</td>
</tr>
<tr>
<td>%</td>
<td>3,3</td>
</tr>
</tbody>
</table>

Si, Cu and Ni are proposed variables of company. However Mo is also incorporated into the variables in order to reach demanded hardness values. The reason for the selection of Mo could be explained with following motives. Firstly the Xu, W. et.al. [11] worked on its effect and made some suggestions regarding suitable compositions. Secondly documentation of MAGMA suggesting not to use more than 2,0% Ni. However Ni does not have strong effect on hardness that means the necessity of higher amounts of Ni. Finally material price is more or less same for Ni and Mo. Beside that the hardness could be arranged in other ways (i.e. decreasing carbon equivalent, decreasing Mn, etc.) but the only variables of the work are Si, Cu and Ni. In that manner replacing Ni with similar costing material is a reasonable choice.
4 Findings and analysis

4.1 Simulation results

There are many factors affecting the results of the simulations. In order to have a better understanding on the effects of simulation settings of MAGMA some of the selections will be shown in following figures.

Differences of inoculation, pouring temperature and filling simulations are explained in next sections. In order to show higher amount of differences between the settings SNL-511 is used. Due to its smaller size, it is easily affected even by tiny variations.

4.1.1 Effect of inoculation

The difference between “Good (In Stream)” and “Fair (Ladle)” inoculation for the same composition is shown in the Figure 20 for the top side of the parts and 21 for the bottom side of the parts.

![Figure 20](image1.png)  
![Figure 21](image2.png)

Figure 20  Hardness results of parts with A) good inoculation, B) fair inoculation.
It is clearly seen that fair inoculation will have problematic areas on thin sections or the edges of the part because of rapid cooling of mentioned areas. Those regions are marked with green, however only some of the areas marked. Nevertheless other areas have same properties. It can be seen that inoculation helps to prevent the carbides on thin sections or edges.

4.1.2 Effect of pouring temperature

The effect of the pouring temperature is shown in the following figures. The pouring temperatures are 1450°C, 1400°C and 1375°C respectively. Some parts are sectioned for better reflection of the results.
Figure 22  Hardness results of 1450°C pouring temperature.
Figure 23    Hardness results of 1400°C pouring temperature.
Analysing the Figure 22 to 24 shows that changing the pouring temperature directly affects the hardness of the parts. It is evident that higher pouring temperatures will cause to have lower hardness values, due to longer cooling period gives more time for complete micro-structure formation.
4.1.3 Effect of filling simulation

As this thesis is focused on finding the correct alloy composition for different sized parts, primary stages are done without the contribution of filling simulations. Running the simulations without a filling option helps to find correct composition faster. For example a simulation with same mesh number finish in 3-4 hours without filling, however running the same simulation with filling will end in 17-18 hours. Below are the results for simulations with and without filling for the same composition (Figure 25).

![Figure 25](image)

A) hardness results without filling  
B) hardness results with filling

As seen above the results between two simulations are not that different. However without filling the simulation gives less realistic results on heat related problems. Sum of all it can be said that simulations without filling will help to reach the goal faster.
4.1.4 Effect of composition

For beginning the simulations a feasible composition is investigated. In their research Xu, W. et.al. [11] proposed a feasible composition with good mechanical properties. Using suggested composition (Table 3) simulations are started with pouring temperature of 1400°C. Although the suggested composition is different than the company’s suggested values, in this manner it is easier to evaluate the results between simulations and research of Xu, W. et.al. Goal for finding a suitable composition is set as achieving hardness values around 220 HB. Below are the results for:

Table 3 Starting composition for the simulations.

<table>
<thead>
<tr>
<th></th>
<th>C</th>
<th>Si</th>
<th>Cr</th>
<th>Cu</th>
<th>Mn</th>
<th>Mo</th>
<th>Ni</th>
<th>P</th>
<th>S</th>
</tr>
</thead>
<tbody>
<tr>
<td>%</td>
<td>3.2</td>
<td>2.0</td>
<td>0.1</td>
<td>1.0</td>
<td>0.55</td>
<td>0.3</td>
<td>0.0</td>
<td>0.05</td>
<td>0.075</td>
</tr>
</tbody>
</table>

Figure 26 Hardness results for SNLN-3056.
Findings and analysis

Figure 27  Hardness results for SNL-517.

Figure 28  Hardness results for SNL-511.
Findings and analysis

It is seen that this composition is feasible for SNLN-3056 (Figure 26) but not suitable for SNL-511 (Figure 28) or 517 (Figure 27). Further simulations on SNLN-3056 are made with molybdenum addition instead of nickel.

On the other hand it was seen that Mo addition was unnecessary for SNL-511 or 517. For the next step copper amount is reduced to the SKF’s composition (Appendix I), which is 0,3%. Also as the proposed compositions are different, simulations of SNLN-3056 and SNL-511/517 could be run separately. Figure 29 shows the results for 0,3% Cu and 0% Mo.

![Figure 29](image)

Figure 29   Hardness results of SNL-511 for 0,3% Cu.

Although the hardness value is decreased, results are still higher than the standard regulations. Then carbon content is set to the SKF values; 3,3%. Figure 30 and 31 show results for new composition.
Figure 30  Hardness results of SNL-511 for 3.3% C and problematic region.

Figure 31  Hardness results of SNL-517 for 3.3% C and problematic regions.
Hardness values of SNL-517 had been lowered to the requirement specifications, but it still shows some minor problems. However SNL-511 has higher hardness values. In order to eliminate heat related problems, addition of graphite promoter alloys are proposed. As a result %Mn for both parts has increased to the SKF values. Result of %Mn increase is shown in Figure 32. In addition to that %Si for both parts has altered.

Figure 32   Hardness results of SNL-511 for 0.75% Mn.

A number of simulations had been run with differing %Si contents. It had seen that a change on silicon content have a higher influence on the hardness values of SNL-511 than SNL-517. On SNL-517 varying amounts of Si content change the amount of undercooled areas, but it was not enough to overcome the problem totally. As a result effects of nickel addition and varying copper contents had started to investigate. Some results are shown in Figure 33 and 34.
Figure 33  Hardness results of SNL-517 for 2.1% Si; 0.4% Cu; 0.35% Ni.

Figure 34  Hardness results of SNL-511 for 2.1% Si; 0.3% Cu; 0.35% Ni.
A feasible composition for SNL-517 had been found with 2,1% Si, 0,4% Cu, 0,35% Ni values. But closely same composition gives higher hardness values for SNL-511. Further simulations are carried on for SNL-511 by the means of lowering the Si, Cu and Ni contents. Some results are shown in Figure 35 to 37.

Figure 35  Hardness results of SNL-511 for 1,9% Si; 0,15% Cu; 0,2% Ni.

Figure 36  Hardness results of SNL-511 for 1,75% Si; 0,1% Cu; 0,1% Ni.
Reasonable result is obtained for SNL-511 with alloy composition of 1.7% Si, 0.1% Cu, 0.15% Ni. In order to arrange same base composition for all the parts further simulations are run for the SNLN-3056. Feasible result is found for 2.1% Si, 1.0% Cu, 0.4% Mo (Figure 38).
After finding satisfactory compositions for all the parts using pouring temperature of 1400°C without filling simulations, new simulations are focused to find more realistic compositions using the real case values.

Finding a reasonable composition for SNLN-3056 was rather easy because of the parts bigger size, which cools down at longer time. Si content for the new tests are fixed at 2.0% as it has the lower effect on mechanical properties according to the Bates, C.E. [10]. After running few tests with varying Mo contents, proposed trial composition is selected for 2.0% Si, 1.0% Cu, 0.5% Mo alloying content. The results are shown in Figure 39-40.

Figure 39  Hardness results of SNLN-3056 for 2.0% Si; 1.0% Cu; 0.5% Mo.
Figure 40  Tensile strength results of SNLN-3056 for 2.0% Si; 1.0% Cu; 0.5% Mo.

For the case of SNL-517 further simulations are continued with varying Si, Cu and Ni values. Selecting criteria for the SNL-517 became finding a less problematic composition with sufficient minimum tensile stress values. Results are shown Figure 41 to 44.

Figure 41  Hardness results of SNL-517 for 2.1% Si; 0.3% Cu; 0.3% Ni.
Findings and analysis

Figure 42  Hardness results of SNL-517 for 1.8% Si; 0.4% Cu; 0.3% Ni.

Figure 43  Hardness results of SNL-517 for 1.8% Si; 0.1% Cu; 0.15% Ni.
Findings and analysis

Figure 44  Minimum tensile stress results of SNL-517 for 1.8% Si; 0.1% Cu; 0.15% Ni composition. Red area shows regions lower than 250 MPa.

Trial casting composition is selected for 1.8% Si, 0.25% Cu, 0.2% Ni alloying contents. Figure 45-46 shows the selection results.

Figure 45  Hardness results of SNL-517 for 1.8% Si; 0.25% Cu; 0.2% Ni.
Figure 46  Minimum tensile stress results of SNL-517 for 1.8% Si; 0.1% Cu; 0.15% Ni.

Many simulations had been executed for finding a suitable composition for SNL-511. Like SNL-517 main target of simulations became finding a composition that leads to fewer undercooled areas. Hardness or minimum tensile stress results were not a problem due to its rather small size. Also during the simulations it appeared that Ni and Cu have similar effects on the hardness results. However Ni addition helps to prevent heat related issues. Some results are shown in Figure 47 to 51.

Figure 47  Hardness results of SNL-511 for 1.8% Si; 0.1% Cu; 0.15% Ni.
Findings and analysis

Figure 48  Hardness results of SNL-511 for 1.6% Si; 0% Cu; 0.1% Ni.

Figure 49  Hardness results of SNL-511 for 1.6% Si; 0.3% Cu; 0% Ni.

Figure 50  Hardness results of SNL-511 for 1.65% Si; 0.05% Cu; 0.05% Ni.
Findings and analysis

Figure 51  Hardness results of SNL-511 for 1,75% Si; 0,1% Cu; 0,15% Ni.

For the trials a composition with 1,7% Si, 0,1% Cu and 0,15% Ni content is selected. Although the hardness values are little bit higher than the targeted values, problematic are less than the many other versions. Moreover in the trials of the suggested alloy compositions for SNL-511 and SNL-517, parts are casted in the same line and both compositions (Alloy-1 and 2) are tried for each two part. Results of SNL-511 are shown in Figure 52-53.

Figure 52  Hardness results of SNL-511 for 1,7% Si; 0,1% Cu; 0,15% Ni.
Figure 53  Minimum tensile stress results of SNL-511 for 1.7% Si; 0.1% Cu; 0.15% Ni.
4.2 Findings

4.2.1 Composition

Compositions are measured from the composition test specimens. The measurements are carried on the spectrometer at SKF Mekan AB. Table 4 shows composition of base melt obtained from induction furnace, target compositions and acquired compositions.

Table 4 Compositions of trial casting alloys

<table>
<thead>
<tr>
<th>BASE MELT</th>
<th>Fe</th>
<th>Cekv</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>% 3.26</td>
<td>1.70</td>
</tr>
<tr>
<td>Co</td>
<td>% 0.005</td>
<td>0.009</td>
</tr>
<tr>
<td>Zn</td>
<td>% &lt;0.001</td>
<td>0.024</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>ALLOY 1</th>
<th>Fe</th>
<th>Cekv</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target composition</td>
<td>Ni: 0.15</td>
<td>Cu: 0.1</td>
</tr>
<tr>
<td>Added materials</td>
<td>Ni</td>
<td>-</td>
</tr>
<tr>
<td>C</td>
<td>% 3.22</td>
<td>1.74</td>
</tr>
<tr>
<td>Co</td>
<td>% 0.005</td>
<td>0.009</td>
</tr>
<tr>
<td>Zn</td>
<td>% &lt;0.001</td>
<td>0.024</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>ALLOY 2</th>
<th>Fe</th>
<th>Cekv</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target composition</td>
<td>Ni: 0.2</td>
<td>Cu: 0.25</td>
</tr>
<tr>
<td>Added materials</td>
<td>Ni</td>
<td>Cu</td>
</tr>
<tr>
<td>C</td>
<td>% 3.22</td>
<td>1.87</td>
</tr>
<tr>
<td>Co</td>
<td>% 0.005</td>
<td>0.010</td>
</tr>
<tr>
<td>Zn</td>
<td>% &lt;0.001</td>
<td>0.027</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>ALLOY 3</th>
<th>Fe</th>
<th>Cekv</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target composition</td>
<td>Ni: 0.0</td>
<td>Cu: 1.0</td>
</tr>
<tr>
<td>Added materials</td>
<td>Cu</td>
<td>Si</td>
</tr>
<tr>
<td>C</td>
<td>% 3.16</td>
<td>1.98</td>
</tr>
<tr>
<td>Co</td>
<td>% 0.005</td>
<td>0.010</td>
</tr>
<tr>
<td>Zn</td>
<td>% &lt;0.001</td>
<td>0.028</td>
</tr>
</tbody>
</table>
4.2.2 Tensile test specimens

Tensile test specimens are machined according to the EN 1561:1997 standard, and tested for the tensile strength and hardness results. The hardness results measured here are just informative values, because company is using the values which are obtained directly from the parts. More information about the test sample preparation is explained at Appendix II. Tensile strength and hardness values of separate cast test samples are given at Table 5.

Table 5  Tensile strength and hardness values of the test specimens of Ø20 mm.

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Tensile strength</th>
<th>Hardness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alloy 1</td>
<td>231 MPa</td>
<td>215 HB</td>
</tr>
<tr>
<td>Alloy 2</td>
<td>291 MPa</td>
<td>218 HB</td>
</tr>
<tr>
<td>Alloy 3</td>
<td>350 MPa</td>
<td>255 HB</td>
</tr>
</tbody>
</table>

4.2.3 Parts

4.2.3.1 Hardness

Measurements are carried out at SKF Mekan AB’s quality department. Hardness tests are carried out after parts are sand-blasted. Test regions and derived results are shown in Table 6.

Table 6  Hardness results of the parts and measuring positions.

<table>
<thead>
<tr>
<th>Position of the hardness measurements</th>
<th>Place 1</th>
<th>Place 3</th>
<th>Place 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hardness Results [HB] (average of samples)</td>
<td>Alloy 1</td>
<td>Alloy 2</td>
<td></td>
</tr>
<tr>
<td>SNL-511</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>227</td>
<td>218,4</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>215,3</td>
<td>216,9</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>209,6</td>
<td>202,7</td>
<td></td>
</tr>
<tr>
<td>SNL-517</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>208,2</td>
<td>219,9</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>206,8</td>
<td>212,5</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>205,8</td>
<td>204,1</td>
<td></td>
</tr>
<tr>
<td>SNLN-3056</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>208,2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>203,4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>207,6</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
4.2.3.2  Simulations with exact trial compositions

Simulations are executed again with the alloy compositions obtained at the company, in order to find differences between the trial and simulation results. New results are shown in Figure 54 to 58.

![Figure 54](image)

Figure 54  Hardness results of SNL-511 for Alloy-1. Top, bottom and sectioned.
Figure 55  Hardness results of SNL-511 for Alloy-2. Top, bottom and sectioned.
Figure 56  Hardness results of SNL-517 for Alloy-1. Top, bottom and sectioned.
Figure 57  Hardness results of SNL-517 for Alloy-2. Top and sectioned.
Figure 58  Hardness results of SNLN-3056 for Alloy-3. In figure B part is sectioned for showing inside of the body.
Accordingly with the lower %C content (or we can say lower CE value) of compositions, hardness results are slightly higher than suggested compositions. Also as a consequent of fair inoculation the parts are very likely to have more undercooled areas. Especially on the SNL-511 with Alloy-1 effects of the fair inoculation is very clear. Furthermore SNL-517 with Alloy-1 is also suffering from undercooling.

Simulation results of microstructural properties are shown in Figure 59 to 63. Table 7 shows the values those are read from hardness measurement position.

Figure 59   Eutectic cell size and lamellar spacing of the SNLN-3056.
Findings and analysis

Figure 60  A) Eutectic cell size B) Lamellar spacing for SNL-517 Alloy-1

Figure 61  A) Eutectic cell size B) Lamellar spacing for SNL-517 Alloy-2

Figure 62  A) Eutectic cell size B) Lamellar spacing for SNL-511 Alloy-1
### Findings and analysis

Figure 63  
A) Eutectic cell size  
B) Lamellar spacing for SNL-511 Alloy-2

Table 7  
Eutectic cell size and lamellar spacing results of the simulations.

<table>
<thead>
<tr>
<th></th>
<th>Eutectic Cell Size [mm]</th>
<th>Lamellar Spacing [µm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>SNL-511 Alloy-1</td>
<td>0,85</td>
<td>12,8</td>
</tr>
<tr>
<td>SNL-511 Alloy-2</td>
<td>0,87</td>
<td>12,9</td>
</tr>
<tr>
<td>SNL-517 Alloy-1</td>
<td>1,05</td>
<td>14,8</td>
</tr>
<tr>
<td>SNL-517 Alloy-2</td>
<td>1,06</td>
<td>14,9</td>
</tr>
<tr>
<td>SNLN-3056</td>
<td>1,6</td>
<td>24</td>
</tr>
</tbody>
</table>
4.2.3.3 **Findings on the parts**

According to the findings of carbide test specimens, it is found that Alloy-1 is very likely to have chills during solidification. Because the inspection of the test specimen showed carbides. On the other hand no such problem was found for Alloy 2 or 3. In the light of test specimens parts are examined for chills. During these examinations chills are found on some areas of SNL-511 with Alloy-1. Problematical areas are marked in Figure 64 and 65.

![Chilled area marked on top of the part](image)

Figure 64 Chilled area marked on top of the part

![Chilled areas marked in a) right side bottom b) bottom.](image)

Figure 65 Chilled areas marked in a) right side bottom b) bottom.

4.2.3.4 **Micro-structures**

For each alloy, samples are prepared from the areas where the hardness measurements are applied. In order to investigate the formations of the alloys, samples are grinded and polished. In Figure 66 to 68 pictures of the flake distributions are shown.
For both of the alloys SNL-517 shows Type A graphite flake distribution (Figure 66-B and 67-B). On the other hand graphite formation of SNL-511 has different distributions (Figure 66-A and 67-A). For alloy 1 graphites distribute in Type E formation and for alloy 2 the distribution is in Type D. Alloy 3 for SNLN-3056 also shows Type A distribution with longer graphite flakes (Figure 68). Further on graphite flake length of the structures are measured (Figure 69 to 71). Findings are shown in Table 8.
For the next step samples are etched with 2% Nital. This step is focused on investigating the lamellar spacing of the pearlites. In figures 72 to 74 microstructures after 2% Nital etching are shown. Measurement of the lamellar spacing is shown in Table 8.
Findings and analysis

Figure 72  Microstructure of Alloy-1 in A) SNL-511, B) SNL-517 etched with 2% Nital.

Figure 73  Microstructure of Alloy-1 in A) SNL-511, B) SNL-517 etched with 2% Nital.

Figure 74  Microstructure of Alloy-3 in SNLN-3056 etched with 2% Nital.

Further on parts polished again and etched with 4% Nital. This step is focused on investigating the formation of the microstructure. In the Figures 75 to 77 microstructures after 4% Nital etching are shown.
Findings and analysis

Figure 75  Alloy-1 etched with 4% Nital for A) SNL-511, B) SNL-517.

Figure 76  Alloy-2 etched with 4% Nital for A) SNL-511, B) SNL-517.

Figure 77  SNLN-3056 with Alloy 3 after 4% Nital etching.

Investigation of the microstructures revealed that in SNL-511 for both alloys formation of the pearlitic microstructures are not completed due to the undercooling. Cementite is still dispersed all along the coarser pearlite lamellas. Conversely the structures of the SNL-517 have completed pearlitic transformation for both alloys. Free cementite precipitated outside the eutectic cells. On the case of SNLN-3056, the structure also shows fully pearlitic formation.
Finally samples are polished again and this time colour etched with picric acid. The purpose of this etching is to relieve the eutectic cells and count them. Figure 78 to 80 shows the microstructures after colour etching. Eutectic cell count measurements are shown in Table-8.

Figure 78     SNL 511 with colour etching for A) Alloy-1, B) Alloy-2.

Figure 79     SNL 517 with colour etching for A) Alloy-1, B) Alloy-2.

Figure 80     SNLN-3056 with colour etching.
Table 8  Findings from the microstructures

<table>
<thead>
<tr>
<th></th>
<th>Average Graphite Flake Length [µm]</th>
<th>Deviation</th>
<th>Average Lamellar Spacing [µm]</th>
<th>Deviation</th>
<th>Eutectic Cell Counts</th>
<th>Average Eutectic Cell Diameter [µm]</th>
<th>Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>SNL-511 Alloy-1</td>
<td>51,2</td>
<td>12,7</td>
<td>1,05</td>
<td>0,22</td>
<td>11</td>
<td>489,7</td>
<td>164,5</td>
</tr>
<tr>
<td>SNL-511 Alloy-2</td>
<td>62</td>
<td>10,4</td>
<td>0,97</td>
<td>0,18</td>
<td>10</td>
<td>509,1</td>
<td>90,5</td>
</tr>
<tr>
<td>SNL-517 Alloy-1</td>
<td>65</td>
<td>14,1</td>
<td>0,8</td>
<td>0,29</td>
<td>7</td>
<td>640,8</td>
<td>35,4</td>
</tr>
<tr>
<td>SNL-517 Alloy-2</td>
<td>71,5</td>
<td>18,2</td>
<td>0,74</td>
<td>0,27</td>
<td>7</td>
<td>682,9</td>
<td>76,3</td>
</tr>
<tr>
<td>SNln 3056</td>
<td>168</td>
<td>39</td>
<td>0,45</td>
<td>0,19</td>
<td>5</td>
<td>888,5</td>
<td>134,2</td>
</tr>
</tbody>
</table>

4.3 Analysis

Differences of hardness values between simulation outputs and trial casting are shown in Table 9.

Table 9  Average differences for hardness values of simulation results and real case results.

<table>
<thead>
<tr>
<th>Part and alloy</th>
<th>Trial casting average of three hardness points</th>
<th>Simulation averages</th>
<th>Difference between simulation and trial cast values</th>
</tr>
</thead>
<tbody>
<tr>
<td>SNL-511 Alloy-1</td>
<td>217,3 HB</td>
<td>223</td>
<td>2,62%</td>
</tr>
<tr>
<td>SNL-511 Alloy-2</td>
<td>212,6 HB</td>
<td>225</td>
<td>5,83%</td>
</tr>
<tr>
<td>SNL-517 Alloy-1</td>
<td>206,9 HB</td>
<td>217</td>
<td>4,88%</td>
</tr>
<tr>
<td>SNL-517 Alloy-2</td>
<td>212,17 HB</td>
<td>218</td>
<td>2,74%</td>
</tr>
<tr>
<td>SNLN-3056</td>
<td>206,4 HB</td>
<td>221,5</td>
<td>7,32%</td>
</tr>
</tbody>
</table>
While interpreting results from Table 9 these issues should be kept in mind:

- Simulation values are interpreted individual, and could differ for each person.

- Simulations are executed with exact temperature. Contrary trial castings could have different pouring temperatures than the simulated, because the melt temperatures didn’t checked during the pouring process. As the pots are filled directly from induction furnace and didn’t wait for the preparations, we could expect the temperature to be higher at the beginning and lower at the finish. It will be expected that different parts could have different results. Also all the casted samples didn’t checked for their hardness. Last but not least the tested samples could be casted hotter than the supposed simulation value. Sum of all simulation values may be evaluated for 3-4 HB lesser.

Differences of hardness values between real case and simulation outputs are between 2.6% to 7.3%. In case of evaluating the simulation values few HB lesser due to higher pouring temperature, differences could be decreased. Then the resulting variation would become 1% to 5%. There is no relation between the deviations of the findings.

Secondly the hardness results of SNL-511 are decreased for Alloy-2 unlike the simulation projections. This phenomenon could be explained with the microstructure of the parts. MAGMA gives the hardness results for a fully pearlitic formation assumption. However the parts have Type D graphite distribution. Although these are fine graphite forms, they are unformed pearlite structures. Existence of these graphites would lead to differences on the expected results of mechanical properties.

Type E graphite formation of the SNL-511 Alloy-1 is an oriented undercooled formation with finer graphites and expected to have rather similar mechanical properties along the investigated region. However Type D of the SNL-511 Alloy-2 is an unoriented formation and it is very likely to have varying mechanical properties across the part. Fine graphite flakes would cause an increase in the hardness values.

Subsequently on the case of SNL-517 the difference of the results within the alloys are different also. It can be explained with the graphite flakes of the microstructure are longer for the Alloy-1 than the Alloy-2. Shorter and increased amount of graphite flakes improve the hardness at higher ratio. Also the pouring temperatures of the samples might be the case again.

According to the data obtained from the microstructure we can analyse effect of size and chemical composition. Increasing size of the parts helps to decrease the tendency of undercooling. We can see this case by analysing the
findings of Alloy-2 from SNL-511 and SNL-517. Both parts have same composition and have the similar hardness value. However average graphite flake is longer for the bigger part. Also average lamellar spacing is decreased. Moreover average eutectic cell diameter is increased. All of these mentioned events could be related with decreased tendency for undercooling. Differences of average lamellar spacing and average eutectic cell size between simulation outputs and trial casting are shown in Table 10.

Table 10 Differences of average lamellar spacing and average eutectic cell size

<table>
<thead>
<tr>
<th></th>
<th>Average Lamellar Spacing [µm]</th>
<th>Average Eutectic Cell Diameter [µm]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Real</td>
<td>Simulation</td>
</tr>
<tr>
<td>SNL-511 Alloy-1</td>
<td>1,05</td>
<td>12,8</td>
</tr>
<tr>
<td>SNL-511 Alloy-2</td>
<td>0,97</td>
<td>12,9</td>
</tr>
<tr>
<td>SNL-517 Alloy-1</td>
<td>0,8</td>
<td>14,8</td>
</tr>
<tr>
<td>SNL-517 Alloy-2</td>
<td>0,74</td>
<td>14,9</td>
</tr>
<tr>
<td>SNLN 3056</td>
<td>0,45</td>
<td>24</td>
</tr>
</tbody>
</table>

Inspection of Table-10 will show big differences between simulations and real case. Especially on the average lamellar spacing case, there are serious differences. For SNL-511 and SNL-517 simulation values are 10 to 20 times bigger than real case. In case of SNLN-3056 it became 50 times. If we put the numerical values aside, the trend of values are also going in reverse directions. In real case average lamellar spacing values are getting smaller with the increasing size of the parts. However simulation results show an increase in values.

In case of average eutectic cell diameter simulation outputs are still higher than trial cast results, yet the trend is in the same direction. Although the measurements of real case are subjective to the individual, the difference of the individuals still won’t be very different than each other.
5 Discussion and conclusions

5.1 Discussion of method

When we compare the simulation and trial casting results, we could see that simulations gave applicable results for the real case. Obtaining the same mechanical results by the means of different alloys is more or less achieved. With the help of the simulations feasible alloying element contents could easily arranged.

5.1.1 Positive and negative aspects of method of action

In order to find feasible results many simulations had to be executed. Running time of the simulations is directly affected by the mesh cell size of the parts. Simulations with low number of mesh cells are finishing faster but the results of these simulations are rather worse. On the other hand quicker simulations support to reach the goal rapidly. In that manner many simulations could be executed for different settings. With the help of small variations in the settings, their effects could be investigated. Better understanding in selections leads to improved results.

Secondly selecting initial values of simulations correctly also helps to reach the goal faster. In my case I had run some simulations with higher pouring temperatures. Although those simulations help me to understand the effect of different pouring temperatures, they became unnecessary for my case. On the other hand during trial castings pouring temperature didn’t checked. For the current situation approximate knowledge about effect of temperature on parts’ hardness values became useful.

Furthermore number of variants is affecting the pace of improvement on the findings. More variants means more simulations and more simulations require more time. Also changing many variants at one step makes the understanding of the results more complex. Although altering one variant for each step would require more simulations, a better understanding of the results would lead to better modifications, which could lead to better results. Additionally adjustment should be in decent ratio. While too small difference would become useless and time consuming, yet too big variance could make the result harder to understand. Also during the selection of variants real life situations must be considered. For example during the melt preparations exact compositions are really hard to achieve.

Last but not least making more casting trials would help to improve the results. A better understanding on the casting process, procedure of melt preparation, mechanical tests and many more real life situations will lead to select better initial values.
5.1.2 What could have done better

Due to the busy production queue at the company some comprises had to be given. If the casting temperatures could have checked for exact values, then the results of simulations and the real life situations could have been better compared. In this case analyse of the results must be done for a range of temperature instead of doing for exact or close temperatures.

Furthermore during the trials, castings are manufactured with ladle inoculation. However for the regular production process in-stream inoculation is used. Although the simulations have option for inoculation type, results could differ from the expected. Probable cause is the lower control of the structure formation.

Also the microstructure investigation could have done for more areas of the parts. By the help of more research on different regions, the results and simulations could be compared in a better level.

Tensile strength properties of the parts are not investigated due to limited amount of time. Specific samples could be prepared from parts and further investigated for the tensile properties. However in current case tensile test bars are separate casted and no simulations are carried on for the research of the test bar. Although these bars are used due to regulations, they are giving weak information for the parts’ tensile properties.

5.1.3 Validity and reliability of results

Results of the simulations seem to have quite good results regarding the undercooled regions of the parts. After the inspection of the parts it was seen that SNL-511 had chilled areas, which is not acceptable to the company. However the main reason of the chilled regions is possibly as the usage of fair inoculation during pouring process. On the other hand simulation results of MAGMA (Figure 55) show that the part would have chilled areas. These areas are located on the thin sections of the bottom side and on edges of the top side.

Moreover simulation results show moderate findings for the hardness’ of the parts. Although the simulation results show higher values than the trial castings, the findings are suitable to further use. However if more precise values are required, simulation results require some corrections before direct use.

The most important topic of the research is the reliability of the simulation results. When we compare the results we could see that simulations gave acceptable results. Most probable source of the differences is assumptions of the program. Mechanical property results are calculated according to fully pearlitic transformation supposition of microstructure.

To sum of all simulation results are valid and practical enough for further use in real life situations. Because the casting trials are made with low control on
structure formation. Despite weak inoculation, varying pouring temperature and less amount of time for melt preparation final hardness values and simulation outputs are close enough. If the trials are made with higher precision probably final results would be much close to the simulation outputs.

5.2 Discussion of findings

Before moving on to analyse of findings, it is better to remind the main purpose of this study. In this thesis work main goal is achieving same hardness value (selected goal is 220 HB) for three different sized casting parts. In order to obtain demanded properties chemical composition is arranged with the variables of silicone (Si), nickel (Ni), copper (Cu) and molybdenum (Mo).

5.2.1 Chemical composition

According to the results of simulations the goal is reached with following compositions:

<table>
<thead>
<tr>
<th>Table 11</th>
<th>Base composition and variables of the research.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>C</td>
</tr>
<tr>
<td>%</td>
<td>3,3</td>
</tr>
</tbody>
</table>

\(w, x, y, z\) are variables for the thesis work.

Table 12 | Suggested compositions according to the simulation results. All values are %wt. |
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Si</td>
</tr>
<tr>
<td>SNL-511</td>
<td>1,7</td>
</tr>
<tr>
<td>SNL-517</td>
<td>1,8</td>
</tr>
<tr>
<td>SNLN-3056</td>
<td>2</td>
</tr>
</tbody>
</table>

However during the trials different chemical compositions are achieved. Regarding the trial casting compositions new simulations are executed with new composition values. It is seen that simulation results and findings of hardness values are quite satisfactory.

Reaching to an acceptable composition is rather easy when the simulations are executed with lower mesh cell numbers. In order to find targeted composition simple simulations would be enough. On the other hand simple simulations would give insufficient results. Yet using simple simulations as a step will help to reach
goal faster.

On the other hand according to the results of tensile test bars Alloy-1 won’t be suitable for further use. This is a result of the quality norm definition. Alloy-1 composition have insufficient tensile on the test bar. Further understanding may be provided with test samples provided from cast parts. However Alloy-1 and 2 resulted in close hardness values for SNL-517. Alloy-1 on this part resulted in shorter graphite flakes and coarser pearlite structure.

5.2.2 Results of MAGMA

Differences on hardness are between 2.6% to 7.3%. The outcomes showed that MAGMA gives pretty good results. However it is evident that the difference on the results of SNLN is clearly higher than the others. Most probable cause of this could be existence of the molybdenum. MAGMA’s molybdenum calculations might have less accurate assumptions.

Another probable cause could be the size of graphite flakes. Graphite flakes in Alloy-3 are 2 or 3 times longer than the ones formed in Alloy-2. Longer graphite flakes could cause a decrease in expected mechanical properties of the parts.

Deviations of hardness differences have no exact pattern. If we think about the smallest and largest deviations, it could make us think that size of the parts are affecting the simulation values. However second worst deviation is measured for the small part again. Also different formation of graphites could lead to misleads in the current case.

There are serious problems with the microstructure formation results. The results are unexpectedly different than the real case. However the hardness calculations of the program could have different assumptions.

Sum of all the results of trials and simulations showed that results of MAGMA are feasible for using without making further researches. In most cases the simulations will give at least 95% correct results. Further understanding on the variants of MAGMA simulations could improve realisation of the values.

5.2.3 Optimization guideline

1. For the beginning a suitable composition should be selected. This composition can be already used composition, software’s default composition from database or an existing composition from a related article.

2. A target for optimisation should be defined.

3. Initial values for the simulations should be defined properly. Simulation settings should be arranged as close as possible to real life case.
4. Simulations should be executed with lower mesh cell count.

5. For each simulation step one or two variants should be altered. Alterations should be made in logical amount. For example an alteration of 0,02% Si would be harder to obtain for a real life scenario. However cerium addition of 0,01% could be arranged during the melt preparation and it will be effective.

6. When targeted values are attained, mesh count of the simulations should be increased.

7. After few simulations with higher mesh cell count, the results should be interpreted.

8. When the targeted values are attained again, simulations should be further continued few steps in positive and negative direction. Because the results could change significantly with a little difference of a variant.

5.3 Conclusions

With the help of MAGMA composition optimisation of different sized parts could be easily optimised in order to achieve same results.

Many simulations are executed with different composition for the silicon, nickel, copper and molybdenum variants. It was seen that Mo additions significantly increase the mechanical properties of the parts. Nickel and copper acts similarly on the hardness values, however nickel addition reduce undercooling tendency at a greater rate.

Good inoculation is vital for the parts with thin sections. Decent inoculation helps to improve the microstructure and helps to get closer results to the simulated values. However MAGMA represents key information about undercooled zones on the part.

Although the microstructure formation results are not valid for the current case, due to inner assumptions MAGMA ensures 95%-97% correct values on hardness results.

5.4 Future work

Better trials at controlled temperature with good inoculation could be performed. In this manner the microstructure of the SNL-511 maybe transformed better. Then a better understanding of the simulations might be ensured.

Microstructures could be studied for different areas of the parts. This will lead to better understanding of the microstructures.

A study might be conducted for the tensile strength properties of the parts and simulations.
6 References

[8] Elkem ASA, Foundry Products Division, \textit{Cast iron inoculation: The technology of graphite shape control}.
References


7 Appendices

Appendix I SKF Mekan AB, Requirement specifications (Kravspecifikationer)

Appendix II EN 1567:1997 European Standard for Grey Cast Iron
GRÅJÄRN

<table>
<thead>
<tr>
<th>Materialbeteckning</th>
<th>Dragprovstav Typ A</th>
<th>Hållfasthet</th>
<th>Hårdhet</th>
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<td>SS-EN symbol</td>
<td>SKF Gjuten Svarvat</td>
<td>Rm N/mm² HB 5/750</td>
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EN-GJL 200 L10 30 20 200-300 (170) -220
EN-GJL 250 V10 30 20 250-350 (180) -230
EN-GJL 300 G10 30 20 300-400 (200)-250**

* V314 30 20 250-350 (180) -230

** För SAAB Ramlageröverfall 911345 gäller HB (190) 245

* Cr-legerat 0125

Dragprovning enligt SS-EN 10002-1.
Rm gäller separat gjuten provstav.

Värden inom parentes är ej bindande.
## SEGJÄRN

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<th>Hårdhet</th>
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<td></td>
<td>min</td>
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<td>EN-G.JS-400-18</td>
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<td>250</td>
</tr>
<tr>
<td>EN-G.JS-600-3</td>
<td>G84</td>
<td>370</td>
</tr>
</tbody>
</table>

Konsekvensklass 2 enligt Volvo standard STD 5060,3 gäller för Rp0,2 min värde 360 N/mm² och förlängning A5 min 10%. Detta krav gäller för de produkter där kraven finns angivna på utfärddad styrplan.

Prostav *separat* gjuten 25 mm *enligt SS-EN 1563*

" svarad 14 mm *enligt SS-EN 1563*

*Dragprovning enligt SS-EN 10002-1*

Hårdhetsfordringarna gäller det framställda gjutgodset.
### MATERIAL

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<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Cr</th>
<th>Cu</th>
<th>Cekv</th>
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<td>2,30</td>
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Max Pb-halt = 0,003 %

Styrgränser, se P1.013

Cekv = C + Si/4 + P/2

Slutanalysen se P1.012
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D = Disa
H = Handformning

* Legering se P1.009  Cekv = C + Si/4 + P/2
Max Pb-halt = 0,003%  Styrgränser se P1.013
### P1.013 Styrgränser-analys

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* =Tillsatsen styrs av SinterCast utrustning termisk analys.

### Åtgärder vid avvikelser:

Då tappningsanalysen (prov 1, 2 o s v) är utanför styrgränsen får gjutning ej ske förrän analysjustering har utförts.

Då slutanalysen (prov 10, 20 o s v) är utanför styrgränsen ska Kvalite (159/211) kontaktas för bedömning av lämplig åtgärd.
English version

Founding
Grey cast iron

Fonderie – Fonte à graphite lamellaire
Gießereiwesen – Gußeisen mit Lamellengraphit

This European Standard was approved by CEN on 1997-05-02. CEN members are bound to comply with the CEN/CENELEC Internal Regulations which stipulate the conditions for giving this European Standard the status of a national standard without any alteration. Up-to-date lists and bibliographical references concerning such national standards may be obtained on application to the Central Secretariat or to any CEN member. The European Standards exist in three official versions (English, French, German). A version in any other language made by translation under the responsibility of a CEN member into its own language and notified to the Central Secretariat has the same status as the official versions. CEN members are the national standards bodies of Austria, Belgium, the Czech Republic, Denmark, Finland, France, Germany, Greece, Iceland, Ireland, Italy, Luxembourg, the Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, and the United Kingdom.
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<td>Annex B (informative) Additional information on the relationship between hardness and tensile strength</td>
<td>16</td>
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<td>Annex C (informative) Additional information on the relationship between tensile strength, hardness and wall thickness of grey iron castings</td>
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<td>Annex D (informative) Bibliography</td>
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## Foreword

This European Standard has been prepared by Technical Committee CEN/TC 190 “Foundry technology”, the secretariat of which is held by DIN.

This European Standard shall be given the status of a national standard, either by publication of an identical text or by endorsement, at the latest by December 1997, and conflicting national standards shall be withdrawn at the latest by December 1997.

Within its programme of work, Technical Committee CEN/TC 190 requested CEN/TC 190/WG 2.10 "Grey cast iron" to prepare the following standard:

EN 1561

Founding – Grey cast irons

According to the CEN/CENELEC Internal Regulations, the national standards organizations of the following countries are bound to implement this European Standard: Austria, Belgium, Czech Republic, Denmark, Finland, France, Germany, Greece, Iceland, Ireland, Italy, Luxembourg, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland and the United Kingdom.
Introduction

Grey cast iron is a casting alloy, iron and carbon based, the latter element being present mainly in the form of lamellar graphite particles.

The properties of grey cast iron depend on the form and distribution of the graphite and the structure of the matrix.

This European Standard deals with the classification of grey cast iron in accordance with the mechanical properties of the material, either tensile strength or hardness.

Further technical data on grey cast irons are given in annexes A to C.

Annex A (informative) contains "Additional information on mechanical and physical properties in addition to tables 1 and 2".

Annex B (informative) contains "Additional information on the relationship between hardness and tensile strength".

Annex C (informative) contains "Additional information on the relationship between tensile strength, hardness and section thickness of grey iron castings".

NOTE: This standard does not cover technical delivery conditions for grey iron castings. Reference should be made to EN 1559-1 and EN 1559-3.

1 Scope

This European Standard specifies the properties of unalloyed and low-alloyed grey cast iron used for castings, which have been manufactured in sand moulds or in moulds with comparable thermal behaviour.

This standard specifies the characterizing properties of grey cast iron by either

a) the tensile strength of separately cast samples, or if agreed by the manufacturer and the purchaser by the time of acceptance of the order, of cast-on samples or samples cut from a casting (see table 1);

or

b) if agreed by the manufacturer and the purchaser by the time of acceptance of the order, the hardness of the material measured on castings (see table 2) or on a cast-on knob.

This European Standard does not apply to grey cast iron used for pipes and fittings according to prEN 877-1.

This European Standard specifies six grey cast irons according to the tensile strength (see table 1) and six grey cast irons according to the Brinell hardness (see table 2).
2 Normative references

This European Standard incorporates by dated or undated reference, provisions from other publications. These normative references are cited at the appropriate places in the text and the publications are listed hereafter. For dated references, subsequent amendments to or revisions of any of these publications apply to this European Standard only when incorporated in it by amendment or revision. For undated references the latest edition of the publication referred to applies.

EN 1559-1
Founding – Technical conditions of delivery – Part 1: General

EN 1559-3
Founding – Technical conditions of delivery – Part 3: Additional requirements for iron castings

EN 10002-1
Metallic materials – Tensile testing – Part 1: Method of test (at ambient temperature)

EN 10003-1
Metallic materials – Brinell hardness test – Part 1: Test method

NOTE: Informative references used in the preparation of this standard, and cited at the appropriate places in the text, are listed in a bibliography, see annex D.

3 Definitions

For the purposes of this standard, the following definitions apply:

3.1 grey cast iron

Iron-carbon cast material in which the free carbon is present as graphite, mainly in lamellar form (flake graphite).

NOTE: Graphite form and distribution are specified in EN ISO 945.

3.2 relative hardness

Quotient of measured hardness to the hardness calculated from the measured tensile strength by means of an empirical relationship (also referred to as RH).

NOTE: RH is influenced mainly by the raw materials, the melting process and the metallurgical working method and usually varies between 0.8 and 1.2.

3.3 relevant wall thickness

Wall thickness for which the mechanical properties apply.

NOTE: The relevant wall thickness is twice the modulus or twice the volume/surface area ratio.

4 Designation

The material shall be designated either by symbol or by number as given in either table 1 or table 2.
5 Order information

The following information shall be supplied by the purchaser:

a) the number of this European Standard (EN 1561);

b) the designation of the material;

c) any special requirements which have to be agreed by the time of acceptance of the order (see EN 1559-1 and EN 1559-3).

6 Manufacture

The method of manufacturing of grey cast iron and its chemical composition shall be left to the discretion of the manufacturer, who shall ensure that the requirements defined in this standard are met for the material grade specified in the order.

NOTE: For grey cast iron to be used in special applications, the chemical composition and heat treatment may be the subject of an agreement between the manufacturer and the purchaser by the time of acceptance of the order.

7 Requirements

7.1 Mechanical properties

In addition to EN 1559-1 and EN 1559-3 the order should specify in an unambiguous manner as to whether the tensile strength measured on separately cast samples or the Brinell hardness measured on the casting is the characterizing property. If it does not do so, then the manufacturer shall characterize the material according to tensile strength.

The characterizing property shall be checked only when this has been agreed by the time of acceptance of the order.

7.2 Tensile properties

7.2.1 Test pieces machined from separately cast samples

The tensile properties of the six grey cast irons defined by tensile strength when measured in accordance with 9.1 using test pieces machined from separately cast samples shall be in accordance with the requirements of table 1.

7.2.2 Test pieces machined from cast-on samples

The tensile properties of test pieces machined from cast-on samples for the six grey cast irons defined by tensile strength shall be in accordance with the requirements of table 1.

7.2.3 Test pieces cut from a casting

If applicable, the tensile properties of test pieces cut from a casting for the six grey cast irons defined by tensile strength shall be agreed between the manufacturer and the purchaser by the time of acceptance of the order and these tensile properties shall be in accordance with the requirements in the agreement.
Table 1: Tensile strength of grey cast irons

<table>
<thead>
<tr>
<th>Material designation</th>
<th>Relevant wall thickness (^1)</th>
<th>Tensile strength (R_m) (^2)</th>
<th>Tensile strength (R_k) (^4)</th>
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<tr>
<td></td>
<td>over mm</td>
<td>mandatory values</td>
<td>anticipated values in casting</td>
</tr>
<tr>
<td></td>
<td>up to and including mm</td>
<td>in separately cast sample (^3)</td>
<td>in cast-on sample</td>
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<td></td>
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<td>min. N/mm(^2)</td>
<td>min. N/mm(^2)</td>
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<td>40</td>
<td>100 to 200(^1)</td>
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<td>2,5(^5)</td>
<td>5</td>
<td>–</td>
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<tr>
<td></td>
<td>5</td>
<td>5</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>20</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>40</td>
<td>150 to 250(^3)</td>
</tr>
<tr>
<td></td>
<td>40</td>
<td>80</td>
<td>110</td>
</tr>
<tr>
<td></td>
<td>80</td>
<td>150</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>150</td>
<td>300</td>
<td>–</td>
</tr>
<tr>
<td>EN-GJL-150 EN-JL1020</td>
<td>5(^5)</td>
<td>5</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>2,5(^5)</td>
<td>5</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>10</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>20</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>40</td>
<td>200 to 300(^3)</td>
</tr>
<tr>
<td></td>
<td>40</td>
<td>80</td>
<td>150</td>
</tr>
<tr>
<td></td>
<td>80</td>
<td>150</td>
<td>140</td>
</tr>
<tr>
<td></td>
<td>150</td>
<td>300</td>
<td>130(^5)</td>
</tr>
<tr>
<td>EN-GJL-200 EN-JL1030</td>
<td>5(^5)</td>
<td>10</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>20</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>40</td>
<td>250 to 350(^3)</td>
</tr>
<tr>
<td></td>
<td>40</td>
<td>80</td>
<td>190</td>
</tr>
<tr>
<td></td>
<td>80</td>
<td>150</td>
<td>170</td>
</tr>
<tr>
<td></td>
<td>150</td>
<td>300</td>
<td>160(^5)</td>
</tr>
<tr>
<td>EN-GJL-250 EN-JL1040</td>
<td>10(^5)</td>
<td>20</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>40</td>
<td>300 to 400(^3)</td>
</tr>
<tr>
<td></td>
<td>40</td>
<td>80</td>
<td>220</td>
</tr>
<tr>
<td></td>
<td>80</td>
<td>150</td>
<td>210</td>
</tr>
<tr>
<td></td>
<td>150</td>
<td>300</td>
<td>190(^5)</td>
</tr>
<tr>
<td>EN-GJL-300 EN-JL1050</td>
<td>10(^5)</td>
<td>20</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>40</td>
<td>350 to 450(^3)</td>
</tr>
<tr>
<td></td>
<td>40</td>
<td>80</td>
<td>260</td>
</tr>
<tr>
<td></td>
<td>80</td>
<td>150</td>
<td>230</td>
</tr>
<tr>
<td></td>
<td>150</td>
<td>300</td>
<td>210(^5)</td>
</tr>
</tbody>
</table>

\(^1\) If a cast-on sample is to be used the relevant wall thickness of the casting shall be agreed upon by the time of acceptance of the order.

\(^2\) If by the time of acceptance of the order proving of the tensile strength has been agreed, the type of the sample is also to be stated on the order (see 8.2). If there is lack of agreement the type of sample is left to the discretion of the manufacturer.

\(^3\) For the purpose of acceptance the tensile strength of a given grade shall be between its nominal value \(n\) (position 5 of the material symbol) and \((n + 100)\) N/mm\(^2\).

\(^4\) This column gives guidance to the likely variation in tensile strength for different casting wall thicknesses when a casting of simple shape and uniform wall thickness is cast in a given grey cast iron material. For castings of non-uniform wall thickness or castings containing bored holes, the table values are only an approximate guide to the likely tensile strength in different sections, and casting design should be based on the measured tensile strength in critical parts of the casting.

\(^5\) These values are guide-line values. They are not mandatory.

\(^6\) This value is included as the lower limit of the relevant wall thickness range.

\(^7\) The values relate to samples with an as-cast casting diameter of 30 mm, this corresponds to a relevant wall thickness of 15 mm.

NOTE 1: 1 N/mm\(^2\) is equivalent to 1 MPa.

NOTE 2: For high damping capacity and thermal conductivity, EN-GJL-100 (EN-JL1010) is the most suitable material.

NOTE 3: The material designation is in accordance with EN 1560.

NOTE 4: The figures given in bold indicate the minimum tensile strength to which the symbol of the grade is related.
7.3 Hardness properties

The Brinell hardness values of the six grey cast irons defined by hardness when measured in accordance with 9.2 shall be as given in table 2.

If it is not possible to use the Brinell test method in accordance with EN 10003-1 alternative test methods may be used, which shall have correlated values with Brinell hardness.

If a casting is ordered on the basis of hardness, the relevant wall thickness and the position of the test shall be agreed upon by the time of the acceptance of the order. The values given for wall thicknesses over 40 mm and up to and including 80 mm in table 2 against the various grades shall be mandatory hardness values for that wall thickness range.

NOTE 1: This subclause establishes hardness grades for grey cast iron.

NOTE 2: This classification is applicable principally where machinability or wear resistance are of importance.

NOTE 3: The hardness values given for smaller thickness ranges ≤ 40 mm are anticipated values only.

NOTE 4: For a relevant wall thickness above 80 mm, grades are not classified by hardness.

<table>
<thead>
<tr>
<th>Material designation</th>
<th>Relevant wall thickness mm</th>
<th>Brinell hardness(1), (2))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>over up to and including</td>
<td>HB 30</td>
</tr>
<tr>
<td>Symbol Number</td>
<td></td>
<td>min.</td>
</tr>
<tr>
<td>EN-GJL-HB155 EN-JL2010</td>
<td>40(^{1}) 80</td>
<td>155</td>
</tr>
<tr>
<td></td>
<td>20 40</td>
<td>160</td>
</tr>
<tr>
<td></td>
<td>10 20</td>
<td>170</td>
</tr>
<tr>
<td></td>
<td>5 10</td>
<td>185</td>
</tr>
<tr>
<td></td>
<td>2.5 5</td>
<td>210</td>
</tr>
<tr>
<td>EN-GJL-HB175 EN-JL2020</td>
<td>40(^{2}) 80 100</td>
<td>175</td>
</tr>
<tr>
<td></td>
<td>20 40 110</td>
<td>185</td>
</tr>
<tr>
<td></td>
<td>10 20 125</td>
<td>205</td>
</tr>
<tr>
<td></td>
<td>5 10 140</td>
<td>225</td>
</tr>
<tr>
<td></td>
<td>2.5 5 170</td>
<td>260</td>
</tr>
<tr>
<td>EN-GJL-HB195 EN-JL2030</td>
<td>40(^{3}) 80 120</td>
<td>195</td>
</tr>
<tr>
<td></td>
<td>20 40 135</td>
<td>210</td>
</tr>
<tr>
<td></td>
<td>10 20 150</td>
<td>230</td>
</tr>
<tr>
<td></td>
<td>5 10 170</td>
<td>260</td>
</tr>
<tr>
<td></td>
<td>4 5 190</td>
<td>275</td>
</tr>
<tr>
<td>EN-GJL-HB215 EN-JL2040</td>
<td>40(^{4}) 80 145</td>
<td>215</td>
</tr>
<tr>
<td></td>
<td>20 40 160</td>
<td>235</td>
</tr>
<tr>
<td></td>
<td>10 20 180</td>
<td>255</td>
</tr>
<tr>
<td></td>
<td>5 10 200</td>
<td>275</td>
</tr>
<tr>
<td>EN-GJL-HB235 EN-JL2050</td>
<td>40(^{4}) 80 165</td>
<td>235</td>
</tr>
<tr>
<td></td>
<td>20 40 180</td>
<td>255</td>
</tr>
<tr>
<td></td>
<td>10 20 200</td>
<td>275</td>
</tr>
<tr>
<td>EN-GJL-HB255 EN-JL2060</td>
<td>40(^{4}) 80 185</td>
<td>255</td>
</tr>
<tr>
<td></td>
<td>20 40 200</td>
<td>275</td>
</tr>
</tbody>
</table>

\(1)\) For each grade, Brinell hardness decreases with increasing wall thickness.

\(2)\) By agreement between the manufacturer and the purchaser a narrower hardness range may be adopted at the agreed position on the casting, provided that this is not less than 40 Brinell hardness units. An example of such a circumstance could be castings for long series production.

\(3)\) Reference relevant wall thickness for the grade

NOTE 1: Information on the relationship between Brinell hardness and tensile strength is indicated in figure B.1 and the relationship between Brinell hardness and relevant wall thickness in figure C.2 of annexes B and C respectively.

NOTE 2: The material designation is in accordance with EN 1560.

NOTE 3: The figures given in bold indicate the minimum and maximum Brinell hardness, to which the symbol of the grade is related and the corresponding reference relevant wall thickness range limits.
8 Sampling

8.1 General

Samples shall be supplied in order to characterize the grade of the material.

If heat treatment is used to modify the properties of the material, then the samples shall be heat treated in the same way as the castings they represent.

8.2 Tensile test

8.2.1 Separately cast samples

The separately cast samples to establish the material grade shall be cast vertically (see figure 1). The moulds shall be either sand moulds or moulds with comparable thermal diffusivity. The moulds may be made for casting several samples simultaneously.

The length \( L \) shall be determined according to the length of the test piece A or B (see 9.1) and the clamping device used.

Other dimensions of the mould shall meet the dimensional requirements of figure 1.

![Diagram of separately cast samples](image)

All dimensions are given in millimetres

**Figure 1: Separately cast samples**

Samples of other dimensions and using other casting procedures may be agreed between the manufacturer and the purchaser for the purpose of representing the properties of particular castings (an indication of the likely values of tensile strength is given in figure C.1).

Samples shall be made from the metal used to produce the castings which they represent and during the same period as when the castings are made.

The frequency of casting the separately cast samples shall be in accordance with the in-process quality assurance procedures adopted by the manufacturer.

The samples shall be stripped from the mould at a temperature not exceeding 500 °C.

**NOTE:** However, the samples may by agreement between the manufacturer and the purchaser be taken from their moulds at a temperature in excess of 500 °C, if the castings are also to be removed at this temperature.
8.2.2 Cast-on samples

The test pieces used for the tests specified in clause 7 shall be machined from a cast-on sample, as indicated in figures 2 or 3. The test pieces shall be in accordance with 7.2.2. The type of sample shall be chosen in such a way as to provide approximately the same cooling conditions as for the casting to be represented. The type of sample and the location of the sample on the casting shall be agreed between the manufacturer and the purchaser. If there is no such agreement, the manufacturer shall decide on the type of sample and it shall be located at a representative position on the casting.

NOTE 1: Two possible sets of sizes are shown in figures 2 and 3, with the larger test piece size option being shown in brackets. The small size set is used for castings less than 80 mm wall thickness and the large size set is used for castings equal to or greater than 80 mm wall thickness.

The length $L$ shall be determined according to the length of the test piece and the clamping device.

NOTE 2: Cast-on samples should only be used when a casting is more than 20 mm thick and the mass is more than 200 kg.

8.2.3 Test pieces cut from a casting

Table 1 shows anticipated minimum values of tensile strength for test pieces cut from a casting with uniform section of simple shape.

NOTE: Values obtained in castings of variable wall thickness can differ from those given in table 1.
All dimensions are given in millimetres

NOTE: For significance of figures in brackets see 8.2.2.

Figure 2: Cast-on sample: Type 1

Figure 3: Cast-on sample: Type 2
8.3 Hardness test

Hardness tests may be carried out on the separately cast samples described in 8.2.1.

Alternatively, the Brinell hardness test may be carried out, by agreement between the manufacturer and the purchaser, on a test piece ("Brinell knob") which is cast on to the casting as shown in figure 4. The position of the Brinell knob, and its size and shape, shall be agreed between the manufacturer and purchaser by the time of acceptance of the order.

In order to carry out the Brinell hardness test, the test piece is removed from the casting, ground on the cut surface and then tested on the ground surface.

![Diagram of Brinell knob](image)

All dimensions are given in millimetres

Figure 4: Example of a Brinell knob

If the casting is heat-treated, the Brinell knob shall not be detached from the casting until the heat-treatment process has been concluded.

9 Test methods

9.1 Tensile test

The tensile test shall be carried out in accordance with the requirements of EN 10002-1, using a test piece in conformance either with figure 5 or figure 6.

The dimensions of the test piece shall conform to the dimensions given in table 3. The gripped parts may be either threaded or plain to suit the clamping device.
Figure 5: Test piece A

Figure 6: Test piece B

NOTE: For the same material, the results achieved using test piece A (symbols table 3) can be slightly higher than those achieved by using test piece B.

Table 3: Dimensions of test pieces A and B

<table>
<thead>
<tr>
<th>Diameter $d$</th>
<th>Thread type for threaded test pieces</th>
<th>Thread length $L_2$</th>
<th>Diameter $d_1$ for plain ends</th>
<th>Threaded test piece A total length</th>
<th>Test piece B parallel length $L_e$</th>
</tr>
</thead>
<tbody>
<tr>
<td>6 $\pm 0.1$</td>
<td>M10</td>
<td>13</td>
<td>8</td>
<td>46</td>
<td>18</td>
</tr>
<tr>
<td>8 $\pm 0.1$</td>
<td>M12</td>
<td>16</td>
<td>10</td>
<td>53</td>
<td>24</td>
</tr>
<tr>
<td>10 $\pm 0.1$</td>
<td>M16</td>
<td>20</td>
<td>12</td>
<td>63</td>
<td>30</td>
</tr>
<tr>
<td>12.5 $\pm 0.1$</td>
<td>M20</td>
<td>24</td>
<td>15</td>
<td>73</td>
<td>36.5</td>
</tr>
<tr>
<td>16 $\pm 0.1$</td>
<td>M24</td>
<td>30</td>
<td>20</td>
<td>87</td>
<td>48</td>
</tr>
<tr>
<td>20 $\pm 0.1$</td>
<td>M30</td>
<td>36</td>
<td>23</td>
<td>102</td>
<td>60</td>
</tr>
<tr>
<td>25 $\pm 0.1$</td>
<td>M36</td>
<td>44</td>
<td>30</td>
<td>119</td>
<td>75</td>
</tr>
<tr>
<td>32 $\pm 0.1$</td>
<td>M45</td>
<td>55</td>
<td>40</td>
<td>143</td>
<td>96</td>
</tr>
</tbody>
</table>

1) The cross-sectional area $S_0$ shall be calculated.

2) Recommended dimensions

NOTE 1: $L_p > L_s$, to suit clamping device.

NOTE 2: The row in bold indicates the preferred dimensions for the test pieces.
9.2 Brinell hardness test

The Brinell hardness test, if required, shall be carried out at an agreed position on the casting in accordance with the requirements of EN 10003-1.

10 Retests

The test shall be disregarded if unacceptable results are obtained which are due not to the quality of the cast iron itself, but to any of the following reasons:

a) faulty mounting of the test piece or defective operation of the testing machine;

b) defective sample or machining of the test piece;

c) casting defects in the test piece, revealed after fracture.

In the above cases, a new test piece shall be taken from the same test unit and the results obtained substituted for those of the defective test piece.

Should the tensile test fail to meet the specified minimum tensile strength requirements, other than for the reasons given above, two retests shall be carried out.

If both retests pass, the material shall be deemed to conform to this European Standard.

If one or both retests fail to meet the specified minimum tensile strength requirement, the material shall be deemed not to conform to this European Standard.
Annex A (informative)

Additional information on mechanical and physical properties in addition to that given in tables 1 and 2

Information on mechanical properties is given in table A.1.

Information on physical properties is given in table A.2.

If agreed by the manufacturer and the purchaser by the time of acceptance of the order alternative test procedures may be used, for example wedge penetration test for assessment of tensile strength.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Symbol</th>
<th>SI-unit</th>
<th>Material designation</th>
<th>Bibliographical references (see annex D)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>EN-GJL-150</td>
<td>EN-GJL-200</td>
</tr>
<tr>
<td>Tensile strength</td>
<td>$R_m$</td>
<td>N/mm²</td>
<td>150 to 250</td>
<td>200 to 300</td>
</tr>
<tr>
<td>0,1% proof stress</td>
<td>$R_{p0.1}$</td>
<td>N/mm²</td>
<td>98 to 165</td>
<td>130 to 195</td>
</tr>
<tr>
<td>Elongation</td>
<td>$A$</td>
<td>%</td>
<td>0.8 to 0.3</td>
<td>0.8 to 0.3</td>
</tr>
<tr>
<td>Compression strength</td>
<td>$\sigma_{cb}$</td>
<td>N/mm²</td>
<td>600</td>
<td>720</td>
</tr>
<tr>
<td>0,1% compression yield point</td>
<td>$\sigma_{0.1}$</td>
<td>N/mm²</td>
<td>195</td>
<td>260</td>
</tr>
<tr>
<td>Bending strength</td>
<td>$\sigma_{bb}$</td>
<td>N/mm²</td>
<td>250</td>
<td>290</td>
</tr>
<tr>
<td>Shear strength</td>
<td>$\sigma_{sb}$</td>
<td>N/mm²</td>
<td>170</td>
<td>230</td>
</tr>
<tr>
<td>Torsional strength</td>
<td>$\tau_{bb}$</td>
<td>N/mm²</td>
<td>170</td>
<td>230</td>
</tr>
<tr>
<td>Modulus of elasticity</td>
<td>$E$</td>
<td>kN/mm²</td>
<td>78 to 103</td>
<td>88 to 113</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>$\nu$</td>
<td></td>
<td>0.26</td>
<td>0.26</td>
</tr>
<tr>
<td>Bending fatigue strength</td>
<td>$\sigma_{bw}$</td>
<td>N/mm²</td>
<td>70</td>
<td>90</td>
</tr>
<tr>
<td>Fatigue limit under reversed tension-compression stresses</td>
<td>$\sigma_{stw}$</td>
<td>N/mm²</td>
<td>40</td>
<td>50</td>
</tr>
<tr>
<td>Fracture toughness</td>
<td>$K_{IC}$</td>
<td>N/mm²</td>
<td>320</td>
<td>400</td>
</tr>
</tbody>
</table>

1) When there are special requirements relating to machinability or magnetic properties, then EN-GJL-100 (EN-JL1010) is used. The required properties can be obtained by means of a structure-changing heat-treatment process. EN-GJL-100 (EN-JL1010) is not cited here.

2) Torsional fatigue strength $\tau_{tw} = 0.42 \times R_m$ [3]

3) Depends on the quantity and form of the graphite as well as on the loading.

4) The following approximately applies: $\sigma_{bw} = 0.35 - 0.50 \times R_m$ [3].

5) The following approximately applies: $\sigma_{stw} = 0.53 \times \sigma_{bw} = 0.26 \times R_m$ [3].

NOTE: 1 N/mm² is equivalent to 1 MPa.
Table A.2: Physical properties in separately cast test pieces with 30 mm as-cast casting diameter

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Symbol</th>
<th>SI-unit</th>
<th>Material designation</th>
<th>Bibliographical references (see annex D)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>$\rho$</td>
<td>g/cm³</td>
<td>EN-GJL-150 (EN-JL1020)</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>EN-GJL-200 (EN-JL1030)</td>
<td>7,10</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>EN-GJL-250 (EN-JL1040)</td>
<td>7,15</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>EN-GJL-300 (EN-JL1050)</td>
<td>7,20</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>EN-GJL-350 (EN-JL1060)</td>
<td>7,25</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>7,30</td>
</tr>
<tr>
<td>Specific heat capacity</td>
<td>$c$</td>
<td>J/(kg · K)</td>
<td>460</td>
<td>[5]</td>
</tr>
<tr>
<td>between 20 °C and 200 °C</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>between 20 °C and 600 °C</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Linear expansion coefficient</td>
<td>$\alpha$</td>
<td>$\mu$m/(m · K)</td>
<td>10,0</td>
<td>[5]</td>
</tr>
<tr>
<td>between −100 °C and +20 °C</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>between 20 °C and 200 °C</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>between 20 °C and 400 °C</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>$\lambda$</td>
<td>W/(m · K)</td>
<td>52,5</td>
<td>[5]</td>
</tr>
<tr>
<td>at 100 °C</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>at 200 °C</td>
<td>51,0</td>
<td>49,0</td>
<td>47,5</td>
<td></td>
</tr>
<tr>
<td>at 300 °C</td>
<td>50,0</td>
<td>48,0</td>
<td>46,5</td>
<td></td>
</tr>
<tr>
<td>at 400 °C</td>
<td>49,0</td>
<td>47,0</td>
<td>45,0</td>
<td></td>
</tr>
<tr>
<td>at 500 °C</td>
<td>48,5</td>
<td>46,0</td>
<td>44,5</td>
<td></td>
</tr>
<tr>
<td>Resistivity</td>
<td>$\rho$</td>
<td>$\Omega$ · mm²/m</td>
<td>0,80</td>
<td>[5]</td>
</tr>
<tr>
<td></td>
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<tr>
<td>Coercivity</td>
<td>$H_c$</td>
<td>A/m</td>
<td>0,77</td>
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<tr>
<td>Maximum permeability</td>
<td>$\mu$</td>
<td>$\mu$H/m</td>
<td>0,73</td>
<td></td>
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<tr>
<td>Hysteresis losses at B = 1 T</td>
<td>$\gamma_{BH}$</td>
<td>J/m³</td>
<td>0,70</td>
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<td>0,67</td>
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</tbody>
</table>

1) When there are special requirements relating to machinability or magnetic properties, then EN-GJL-100 (EN-JL1010) is used. The required properties can be obtained by means of a structure-changing heat-treatment process. EN-GJL-100 (EN-JL1010) is not cited here.
Annex B (informative)

Additional information on the relationship between hardness and tensile strength

Hardness and tensile strength as well as Young’s modulus and the modulus of rigidity of grey cast iron of a given grade are approximately related to each other. In most cases, an increase in the value of one property results in an increase in the values of other properties [7] to [9] (see annex D). The following empirical relationship between hardness and tensile strength exists:

\[ \text{HB} = \text{RH} \times (A + B \times R_m) \]

Commonly accepted values for the constants are:

\[ A = 100, \ B = 0.44 \ [10], [11] \]

The factor RH is called relative hardness. This parameter has been found to vary between 0.8 and 1.2. Because of the variation in relative hardness it is difficult to give definitive limits in a standard for both tensile strength and hardness (see figure B.1). More details concerning RH are discussed in literature [10] to [17] (see annex D).

The factor RH is influenced mainly by the raw materials, the melting process and the metallurgical working method. Within one foundry these influences can be maintained nearly constant. The manufacturer can therefore indicate both hardness and the corresponding tensile strength.

![Graph showing relationship between Brinell hardness and tensile strength](image)

| a) Brinell hardness, HB |
| b) Tensile strength \( R_m \), N/mm² |
| c) Relative hardness, RH |

NOTE: 1 N/mm² is equivalent to 1 MPa.

Figure B.1: Relationship between Brinell hardness and tensile strength of grey cast iron
Annex C (informative)

Additional information on the relationship between tensile strength, hardness and wall thickness of grey iron castings

Figure C.1 provides additional general information on the expected relationship between minimum tensile strength and relevant wall thickness. Figure C.2 provides information on average Brinell hardness and relevant wall thickness of castings.

Not all castings can be produced in any material hardness grade given in table 2 for any relevant wall thickness, and this is reflected in figure C.2. To meet the requirements of any hardness range, more than one material grade can be used, depending on the relevant wall thickness involved.

This illustrates the importance of reaching an agreement between the manufacturer and the purchaser on the specification of the hardness required in castings and also the location where a hardness test should be carried out.

![Graph showing relationship between tensile strength and hardness]

a) Tensile strength $R_m$, N/mm$^2$
b) Relevant wall thickness, mm

NOTE: 1 N/mm$^2$ is equivalent to 1 MPa.

Figure C.1: Examples of relationship between minimum values of the tensile strength and the relevant wall thickness of simple shaped castings
a) Brinell hardness HB 30
b) Relevant wall thickness, mm

Figure C.2: Typical relationship between average values of the Brinell hardness and the relevant wall thickness of simple shaped castings
Annex D (informative)

Bibliography

In the preparation of this European Standard, use was made of a number of documents for reference purposes. These informative references are cited at the appropriate places in the text and the publications are listed hereafter.

prEN 877-1
Cast iron pipes and fittings, their joints and accessories for the evacuation of water from buildings – Part 1: Technical specifications

EN 1560
Founding – Designation system for cast iron – Material symbols and material numbers

EN ISO 945
Cast iron – Designation of microstructure of graphite (ISO 945 : 1975)


