THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

INFLUENCES OF THE GRAPHITE PHASE ON ELASTIC AND PLASTIC DEFORMATION BEHAVIOUR OF CAST IRONS

TORSTEN SJÖGREN

SCHOOL OF ENGINEERING
JÖNköPING UNIVERSITY

Department of Mechanical Engineering
Component Technology - Castings
SCHOOL OF ENGINEERING, JÖNköPING UNIVERSITY

INSTITUTE OF TECHNOLOGY
LINKÖPING UNIVERSITY

Department of Management and Engineering
Division of Engineering Materials
LINKÖPING UNIVERSITY

Jönköping, Sweden 2007
Influences of the Graphite Phase on Elastic and Plastic Deformation Behaviour of Cast Irons

TORSTEN SJÖGREN

Department of Mechanical Engineering
Component Technology-Castings
School of Engineering, Jönköping University
SE-551 11 Jönköping, Sweden
torsten.sjogren@daros.se

Copyright © TORSTEN SJÖGREN, 2007

Linköping Studies in Science and Technology
ISSN 0345-7524
Dissertations, No. 1080

Department of Management and Engineering
Division of Engineering Materials
Linköping University
SE-581 83 Linköping, Sweden

Cover image: Stress-strain curves and corresponding graphite morphologies for different cast iron grades.

Printed in Sweden by
Chalmers Reproservice
Göteborg, 2007
INFLUENCES OF THE GRAPHITE PHASE ON ELASTIC AND PLASTIC DEFORMATION BEHAVIOUR OF CAST IRONS

TORSTEN SJÖGREN

ABSTRACT

The amount and morphology of the graphite phase largely controls the resulting properties of cast iron. For instance, in flake graphite cast irons the mechanical properties are low while the thermal conductivity is high. This is in contrast with spheroidal graphite cast irons where the mechanical properties are high and the thermal conductivity is low. These differences are due to the different graphite morphologies and must be accounted for in the design work and material selection of cast iron components. In this work the influence of the graphite phase on the elastic and plastic deformation behaviour of cast irons has been studied.

The material grades studied originate from castings for marine diesel engine piston rings with different chemical analyses. Two groups of pearlitic cast iron materials were studied; one with differences in graphite morphology and one with grey irons that differed in graphite content. For these different material grades the mechanical properties were correlated to microstructural parameters. In addition to standard uniaxial tensile tests, acoustic emission measurements were used for the study of deformation.

When studying the modulus of elasticity of the cast iron it was found that the modulus of elasticity of the inherent graphite phase depends on the roundness of the graphite particles and is due to the strong anisotropy of the graphite phase. A linear correlation between nodularity and the modulus of elasticity of the graphite phase was derived. This correlation made it possible to account for the anisotropy of the graphite phase in the model used. By applying the linear function when modelling the effective modulus of elasticity, a high accuracy between experimental and theoretical values was achieved.

Another factor affecting the elastic response when subjecting a cast iron component to tensile load was found to be the plastic deformation that actually occurs at very low strains for all of the studied cast iron grades. It was observed that the plastic deformation in the low strain elastic region, quantified by using acoustic emission measurements, increased linearly with decreasing modulus of elasticity. These measurements showed that the amount of plastic deformation in the elastic region was largely controlled by the graphite morphology. It was concluded that as the roundness of the graphite particles increases, the plastic deformation activity in the elastic region decreases.

The plastic deformation activity continued linearly into the pronounced plastic region of the tensile tests. A decrease in roundness or increase in graphite fraction resulted in an increase of the amount of plastic deformation and the strain hardening exponent. A dependence between strength coefficient and graphite fraction was observed. Models for the flow curves for pearlitic cast irons were developed and shown to accurately reproduce the observed experimental curves.

The surveys performed and conclusions from this thesis will be helpful in the design of new cast iron materials.

**Keywords:** Cast iron, flake graphite, compacted graphite, spheroidal graphite, elastic deformation, plastic deformation, modulus of elasticity, graphite modulus of elasticity, strength coefficient, strain hardening exponent, acoustic emission.
ACKNOWLEDGEMENTS

I would like to express my gratitude to:

My supervisor professor Ingvar L Svensson for guidance and support throughout this work.

All my colleagues at Daros Piston Rings AB for their support and friendship.

All my colleagues at the Department of Mechanical Engineering at Jönköping University.

Dr. Daniel Holmgren for fruitful discussions and a lot of fine Mössebo-humour.

Dr. Steve Dawson for reviewing some of the supplements included in this thesis.

Dr. Peter Vomacka for good coaching in the early years of my PhD studies.

My good old friend Dr. Jonas Persson and my colleague Dr. Magnus Wessén for giving me useful comments on the thesis manuscript.

Mikael Cederfeldt for providing an excellent Word template for this thesis.

My good friend Mikael Baronowsky for helping me with graphical problems.

The staff at the Library of Jönköping University for their rapid delivery of technical literature.

Professor Sten Johansson, professor Torsten Ericsson and Ingmari Hallkvist at the Division of Engineering Materials, Linköping University for good administration and support during my PhD studies.

Daros Piston Rings AB and The Knowledge Foundation (KK-stiftelsen) for financial support of this project.

My Family, Annalena, David and Ida for being who you are and for all the fun we have together.

Torsten Sjögren
Borås, April 2007
SUPPLEMENTS

The following published and appended papers constitute the basis of this dissertation. In the text the appended papers are referred to by roman numerals.

Where nothing else is stated, Sjögren is the main author and Svensson has been the adviser and has critically reviewed the paper.


Sjögren was the main author and evaluated the simulations and compared it with experiments. Wessén implemented the model used into MAGMAiron. Schäfer performed the simulation.

Sjögren evaluated the mechanical properties of the tested materials. The paper was written jointly by all the authors.
TABLE OF CONTENTS

CHAPTER 1: INTRODUCTION........................................................................................................ .......... 1
   1.1 THE USE AND THE PROPERTIES OF CAST IRONS.................................................................1
   1.2 CHARACTERISATION OF THE GRAPHITE PHASE.................................................................4
   1.3 THE DEFORMATION OF CAST IRONS.....................................................................................5
   1.4 MODELLING THE DEFORMATION BEHAVIOUR OF CAST IRONS...........................................8

CHAPTER 2: RESEARCH APPROACH........................................................................................... 11
   2.1 AIMS AND CONTENTS OF THIS THESIS...............................................................................11
   2.2 EXPERIMENTAL TECHNIQUES.............................................................................................12

CHAPTER 3: SURVEY ..................................................................................................................... 19
   3.1 MATERIAL PROPERTIES OF MARINE DIESEL ENGINE PISTON RINGS (SUPPLEMENT I)......19
   3.2 PROPERTIES OF THE CAST IRON MATRIX (SUPPLEMENT VIII)......................................21
   3.3 THE DEFORMATION BEHAVIOUR OF CAST IRONS (SUPPLEMENTS II, III, IV, V, VIII).......22
   3.4 MODELLING THE MODULUS OF ELASTICITY OF CAST IRONS (SUPPLEMENTS III, VII)......31
   3.5 MODELLING THE STRAIN HARDENING EXPONENT AND STRENGTH COEFFICIENT OF CAST IRONS (SUPPLEMENT V) ...........................................................................................................35
   3.6 MODELLING THE ELASTIC AND PLASTIC STRESS-STRAIN BEHAVIOUR OF CAST IRON (SUPPLEMENT VI)..........................................................................................................................37

CHAPTER 4: CONCLUDING REMARKS .................................................................................... 41

CHAPTER 5: FUTURE WORK ....................................................................................................... 43

APPENDED PAPERS .................................................................................................................... 51
CHAPTER 1

INTRODUCTION

CHAPTER INTRODUCTION
This chapter gives a brief theoretical background to cast irons, their properties and deformation behaviour. It also discusses how different cast iron grades are characterised regarding their graphite morphology and matrix. The theoretical background aims to define the frame of reference for the research questions that this dissertation enlightens.

1.1 THE USE AND THE PROPERTIES OF CAST IRONS
Cast iron components are widely used in industry all over the world, and of the total world tonnage of castings produced, approximately 70 % are made from cast iron (2005) [1]. The Swedish production of cast iron components is in the order of 257 000 tonnes/year (2006) [2]. Of the total production in Sweden, 72 % is flake graphite cast iron (FGI), 21.5 % is spheroidal graphite cast iron (SGI) and malleable iron, 4 % is compacted graphite cast iron (CGI) and the remaining 2.5 % is white iron. The tendency in Sweden during recent years is that the cast iron production is increasing, and a comparison between the production in 2003 and 2006 shows an increase of approximately 19 % [2]. The reasons for the domination of cast iron in cast products derive from the wide range of mechanical and physical properties which can be produced, and its competitive price.

One of the largest cast iron component users is the diesel engine manufacturers where cylinder heads, cylinder liners and piston rings (for marine diesel engines) are typical

![Flake graphite.](image1)
![Compacted graphite.](image2)
![Spheroidal graphite.](image3)

**FIGURE 1. Different graphite morphologies observed in deep etched cast irons.**

One of the largest cast iron component users is the diesel engine manufacturers where cylinder heads, cylinder liners and piston rings (for marine diesel engines) are typical.
components. In the case of cast iron materials for piston rings, which are focused on in this
thesis, FGI, CGI and SGI cast irons are used with a predominantly pearlitic matrix. The
different graphite morphologies are shown in Fig. 1. In Fig. 2a a typical pearlitic matrix
structure found in piston rings is shown. To improve the wear resistance of the piston ring
material, a well dispersed precipitation of cementite is desired as shown in Fig. 2b (white
areas). The material grade in Fig. 2 is Daros Piston Rings’ compacted graphite cast iron
grade denominated Darcast™.

![Pearlitic matrix.](image1)
![Free cementite (white).](image2)

**FIGURE 2.** Compacted graphite cast iron used in piston rings.

The properties of cast irons are mainly controlled by the shape of the graphite particles in
combination with the matrix constituents, and wide spectrum of properties are observed
for the different cast iron grades. To optimise the properties of a particular cast iron
component, a compromise is probably necessary between, e.g., mechanical and thermal
properties, since these are inversely proportional, i.e., high mechanical strength is
accompanied by low thermal conductivity, and vice versa. The main reason for this
difference in properties is the shape of the graphite particles and the high anisotropy of the
graphite phase.

The natural growth morphology of the graphite phase in liquid iron leads to the spheroidal
shape, and lamellar or compacted growth is a modified growth mode (see Fig. 1). The
modifiers are oxygen and sulphur which affect the growth through a surface adsorption
mechanism [3]. The different morphologies and distributions of the graphite phase
observed in different cast iron grades are achieved by varying a set of parameters, which
basically are; inoculation, melt treatment, chemical composition, solidification rate and
heat treatment.

The graphite phase has diverse properties in the two main crystallographic directions (see
Fig. 3) considering, e.g., thermal conductivity and modulus of elasticity. In the literature,
values of the overall graphite modulus of elasticity are found to be widespread and values
from 4.17 GPa to 303 GPa exist [4-8]. By using nano-indentation analyses in which the
force versus indentation-depth curve for the graphite phase is analysed, the elastic
modulus has been determined by Fukumasu et al. [9]. For a compacted graphite cast iron
sample Young’s modulus of the graphite phase was found to be 23±3 GPa. For the
different crystallographic directions of the graphite, Dryden and Purdy [10] present values
of the modulus of elasticity where the A- and C-axis directions (as seen in Fig. 3) have a modulus of elasticity of 1060 GPa and 0.18 GPa, respectively. The reason for the large difference is the atomic bonding forces, where the in-plane bonding consists of strong covalent bonds and the bonding between the basal planes are weak van der Waals forces [10]. The hexagonal structure of a graphite plane and the sheeted structure are shown in Fig. 3.

**Figure 3. The crystallographic structure of graphite [11].**

Regarding the tensile strength of the graphite phase, various reports give values ranging from 20 GPa to 45 GPa [12, 13].

The amount and shape of the graphite phase also affect the plastic deformation behaviour of cast iron. A higher amount of graphite lowers the material strength and the sharp, lamellar graphite particles observed in grey iron give rise to non-linear deformation behaviour. Even in ductile iron, plastic deformation takes place concurrent with linear elastic deformation [14].

The matrix type achieved, most commonly pearlite and/or ferrite, is particularly affected by the chemical composition, inoculation and cooling conditions. Depending on the matrix type the resulting properties of the cast iron are affected, though the graphite properties influence them to a greater extent. The most common matrix in FGI grades is pearlite and in the case of CGI and SGI ferrite grades are also used.

The mechanical properties of the different matrices are controlled by e.g. alloying and cooling rate which may alter the pearlitic interlamellar spacing, pearlite colony size and the ferrite grain size. For a pearlitic matrix the yield strength is controlled by the interlamellar spacing, pearlite colony size, prior austenite grain size and solid solution strengthening from alloying [15-17]. The strengthening by interlamellar spacing is due to the impediment of the dislocation movement within the ferrite occurring from the cementite lamellas [18].

All graphitic cast irons contain relatively high concentrations of Si (1-3 wt %), which increases the graphitization potential strongly. The addition of Si also increases the strength of the ferritic matrix by solid solution strengthening and reducing the grain size. Per each added wt % Si in the ferritic matrix the yield strength increases by approximately 45 MPa [19].
The literature concludes that Young’s modulus of steel, which the matrix can be regarded as, is relatively insensitive to changes in microstructure and 200-210 GPa is the expected range independent of matrix type [20].

1.2 CHARACTERISATION OF THE GRAPHITE PHASE

To correlate the graphite phase with the mechanical properties of cast iron, the graphite particles are characterised according to shape by several different parameters. The most widely used parameters are roundness, nodularity and aspect ratio. This way of describing the graphite phase does not consider the complex 3D-interconnection of flake and compacted graphite but still it is the best practice of today.

The \textit{roundness} value characterises each graphite particle as a ratio of the particle area and the area of a circumscribed circle as described by Eq. (1).

\begin{equation}
\text{Roundness} = \frac{4}{\pi} \cdot \frac{A}{l_{\text{max}}^2}
\end{equation}

where $l_{\text{max}}$ is the maximum intercept length of a graphite particle and $A$ is the sectional area of the graphite particle in an arbitrarily chosen cross-section. The overall roundness is calculated as the mean roundness value of all graphite particles studied. For graphite structures of perfectly spherical shaped graphite the roundness value is unity and for flake graphite structures with very long and thin graphite particles the value is close to zero. In FGI the graphite particles have a low roundness, typically less than 0.25, and are interconnected within the eutectic cell. For the CGI grade the roundness is intermediate, typically between 0.25 and 0.50, and the graphite phase is interconnected within the eutectic cell. In the case of SGI the graphite appears as discrete, non-interconnected particles with an overall roundness above 0.60.

When considering the \textit{nodularity} of a cast iron, which is especially used when studying compacted graphite cast irons, this parameter is based on the ratio between the area fractions of specific roundness ranges (for which the graphite particles are considered as nodular shaped) to the total area fraction of graphite. This is described in Fig. 4 and by Eq. (2) according to SinterCast [21];

\begin{equation}
\text{Nodularity} = \frac{\sum A_{\text{Nodular}} + 0.5 \cdot \sum A_{\text{Intermediates}}}{\sum A_{\text{Particles}>10\,\mu\text{m}}} \cdot 100
\end{equation}

For CGI grades the nodularity is typically in the range 0-10 %, for a SGI grade the nodularity is approaching 100 % and for FGI grades the nodularity value throughout this thesis, is defined as -100 %. In the case of FGI, SinterCast uses a range from -1 to -5 % to describe the amount of flake graphite patches existing in the otherwise compacted graphite structure [21]. According to SinterCast, -5 % nodularity describes a fully lamellar graphitic structure.

The graphite particles are sometimes described by their \textit{aspect ratio} (AR) where the ratio between width and length of the graphite particle gives this measure.
A large number of cast iron components are used in the automotive industry. In its application environment the cast iron component is often subjected to a combination of mechanical and thermal loads. These loads will affect the component and lead to elastic and plastic deformation. As summarized by Angus [14] the deformation of cast iron and its ability to accommodate strain consists of the following four components:

1. Purely elastic deformation of the matrix.
2. Plastic deformation of the matrix at points of high stress.
3. Recoverable strain due to the opening of the graphite cavities.
4. Permanent strain associated with the opening up of the cavities.

These four components are thus responsible for the elastic and plastic region observed in the strain response upon loading of cast iron components. In Fig. 5 the different components, numbered according to the listing above, are shown as occurring on loading and subsequently unloading of an FGI tensile test sample.
From tensile tests several mechanical properties can be determined, such as; ultimate tensile strength, yield strength (0.2 % proof stress) and modulus of elasticity. On loading of FGI the plastic deformation starts immediately, thus no truly elastic response exists [14]. This non-linear deformation behaviour makes Young’s modulus inapplicable. Due to this, a tangent or secant modulus, specified at a certain stress level, is used for FGI grades.

The cold rolled steel is taken from Fang et al. [22].
One way of studying the strain response of a material is described by Fang et al. [22] where a so-called hyperbolic plot is used to determine the modulus of elasticity. A hyperbolic plot for different cast iron grades and cold rolled steel is shown in Fig. 6. Making this kind of hyperbolic plots for cast iron stress-strain data, the elastic region is seen as a plateau which might have a weak upward slope due to the localized plasticity occurring at the matrix/graphite interface. The upward slope is also affected by the matrix constituents, where localized yielding of a pearlitic matrix occurs at higher values of applied strain compared to a ferritic matrix [22]. The appearance of the plateau is strongly affected by the morphology of the graphite phase, as seen for the cast irons in Fig. 6. For flake graphite morphologies a plateau does not even exist, since linear elastic behaviour does not occur due to the immediate start of plastic deformation. As shown in Fig. 6 this type of plotting clearly distinguishes between the different regions of deformation and is a useful tool for determination of the modulus of elasticity and the strain level at which yielding starts. The inverse of the plateau value of the hyperbolic plot in Fig. 6 equals the modulus of elasticity or, more correctly, the tangent modulus. The tangent modulus versus the stress, for the cast irons in Fig. 6, is plotted in Fig. 7.

**FIGURE 7.** Tangent modulus versus stress for three different cast iron grades.

Subsequent to localized yielding of the matrix on loading, micro-cracking and macro-cracking of the matrix occurs. In FGI and CGI these cracks easily proceed through the eutectic cells at low additional applied strain due to the interconnected graphite phase, and are halted when reaching the cell boundaries separating the eutectic cells. Furthermore, the fracture resistance increases as the width of the matrix bridges, separating the graphite segments in adjacent eutectic cells, increases. In ductile iron, decohesion of the graphite nodules takes place at very low strain, far before the initiation of cracks [23].
1.4 MODELLING THE DEFORMATION BEHAVIOUR OF CAST IRONS

The elastic and plastic deformation of any material can be described by Young’s modulus, $E$ (MPa), the strength coefficient, $K$ (MPa), and the strain hardening exponent, $n$. The Hollomon equation [24], Eq. (3), describes the plastic deformation behaviour of a material.

$$\sigma = K(\varepsilon_{pl})^n$$

The $K$ and $n$ parameters can be determined from a log-log plot of the true stress-true strain data as shown in Fig. 8, depicting flow curves from a ductile iron and a grey cast iron. The $n$-value corresponds to the slope of the curve and the $K$-value to the true stress at a true strain of unity. Fig. 9 shows how different materials’ deformation behaviour can be described by altering the $n$-value. A strain hardening coefficient of 0 describes an ideal plastic material, i.e., the material flows when a certain stress condition is reached. If $n=1$ the curve describes an ideal elastic solid, i.e., a linear elastic material (which is considered as a special case of Eq. (3)). For most metallic materials $n$ varies between 0.10 and 0.50 as illustrated in Fig. 9.

Using the Hollomon equation (Eq. (3)) together with Hooke’s law ($\sigma = E \cdot \varepsilon$) Eq. (4) is attained. With Eq. (4) the full elastic-plastic stress-strain curve can be described.

$$\varepsilon_T = \varepsilon_{el} + \varepsilon_{pl} = \frac{\sigma_T}{E} + \frac{\sigma_T^{1/n}}{K^{1/n}}$$

where $\varepsilon$ is the strain, $\sigma$ the stress (MPa), $E$ Young’s modulus (MPa), $n$ the strain hardening exponent and $K$ is the strength coefficient (MPa). The indices $T$, $el$ and $pl$ refer to true, elastic and plastic, respectively.

The Hollomon equation (Eq. (3)) is the most widely used expression to describe the flow curve, and is the equation used throughout this thesis, but other models for modelling flow curves exist in the literature [25-27].

Considering the graphite particles throughout the matrix as dispersed discontinuities, these will affect the strain response on loading by lowering the effective modulus of elasticity.
The magnitude of this reduction is dependent upon the morphology and amount of the graphite phase [14]. When trying to estimate the effective modulus of elasticity there are essentially two approaches; the bound concept and the model concept, where the bound concept results in an upper and a lower bound in between which the effective modulus of elasticity is expected, and the model concept which results in a single approximate value of the effective modulus of elasticity, respectively.

In the literature, first-order and second-order bound equations for the determination of the modulus of elasticity exist as described by Hashin et al. [28] and Ondracek [29]. First-order bound equations treat the material as two phased (rule of mixtures), while the second-order bounds take into account that the material is two-phased and assumes the phases are isotropic, thus no geometrically prescribed microstructural parameters are included [29]. The literature also treats model equations which take into account various numbers of microstructural parameters. In models for composites and cast irons [29-32] inclusions, which in the case of cast irons are the graphite particles, are substituted by an ellipsoidal model where the shape of the mean inclusion corresponds to the aspect ratio value of the ellipsoid. For the models suggested by Mazilu et al. [31] and Boccaccini [32] the orientation of the ellipsoid relative to the stress direction is also taken into account.

Boccaccini modelled the effective modulus of elasticity of cast iron and compared the simulated (modelled) values with experimental values with an estimated average error of 16 %. Boccaccini used values of 8.5 GPa for the graphite modulus of elasticity and 206 GPa for the matrix modulus of elasticity [32].

Concerning the plastic deformation of cast irons, data and correlations for, e.g., yield strength, hardness and ultimate tensile strength versus microstructure, cooling rate and chemical composition exist in the literature [33-35]. For the plastic deformation parameters, i.e., strength coefficient and strain hardening exponent, describing how the material deforms when a load is applied, no correlations to graphite amount (carbon equivalent) or graphite morphology are found in the literature. The literature does though present plastic deformation parameters for different cast iron grades [36 (Ductile Iron), 37 (Austempered Ductile Iron), 38 (Ferritic CGI)]. These references present plastic deformation parameters separately for each material grade without any aim to study how graphite amount and graphite morphology affect the different parameters.
CHAPTER 2

RESEARCH APPROACH

CHAPTER INTRODUCTION

Initially, this chapter presents the aims of this thesis work and describes the contents and focus of the appended papers. Additionally, a description of the various different experimental techniques used is included.

2.1 AIMS AND CONTENTS OF THIS THESIS

Initially, the primary aim of this project was to study the properties of cast iron and how the properties depend on, and can be controlled by, controlling the microstructure. Since the thesis work has been performed at Daros Piston Rings AB the properties of importance of the cast iron base material covers mechanical and thermal properties as well as tribological properties. During the course of the project an emphasis on mechanical properties, especially the elastic and plastic deformation behaviour, and the influence of the amount and morphology of the graphite phase has been established.

The study of the deformation behaviour of cast irons in this thesis work is limited to consider fully pearlitic cast irons tested at room temperature in uniaxial tension.

The thesis contains eight supplements in which the research performed is reported. In Supplement I the production of high-performance piston rings is described. This gives an introduction to the complexity of piston rings and displays the need of expertise in different areas to produce piston rings with an optimization of the desired properties. Supplement I also deals with the demands on mechanical, thermal and tribological properties of the cast iron base materials used in marine diesel engine piston rings. In addition to the properties of the base materials of the piston ring, piston ring coating and piston ring geometry is also treated.

Supplements II - VIII treat the deformation behaviour of cast irons. These supplements describe different aspects of this subject. In the studies treated in these supplements, essentially the same sets of cast iron materials are examined. The materials are divided into two groups where one group covers a variety of nodularities, from FGI (-100 % nodularity) to SGI (~100 % nodularity), and another group that deals with FGI with differences in carbon equivalent (CE), covering a range from hypoeutectic (3.23 wt %) to eutectic (4.32 wt %) composition.

Comparing the mechanical properties of an FGI and a CGI grade it was observed that the mechanical properties of the FGI grade were lowered as the coarseness of the microstructure decreased, which was in contrast to the CGI grade. The reasons for these
RESEARCH APPROACH

Differences in mechanical properties between FGI and CGI are discussed in Supplement II.

To further understand the differences in mechanical properties and deformation behaviour occurring when changing the amount and morphology of the graphite phase, an acoustic emission technique was used in addition to standard mechanical properties testing. This study is described in Supplement IV and discusses the cast iron deformation behaviour.

When studying the properties of cast irons it is often desired to be able to predict the mechanical properties from the characteristics of the microstructure. This is achieved by using models where the microstructure is described by some parameters combined with assumed properties of the included phases. Supplement III describes estimations of the modulus of elasticity for the materials studied by the use of different bound and model equations. This survey provides a basis for the understanding of how the modulus of elasticity of the graphite phase is altered depending on the graphite morphology and how this affects the effective modulus of elasticity of cast irons.

In Supplement VII the modulus of elasticity has been simulated with the help of the control volume based finite difference method software, MAGMASoft. The models presented in Supplement III were implemented into this software and the survey shows that a good agreement between simulated and actual values is possible to achieve.

Supplement V focuses on the plastic deformation of different cast iron grades. Correlations for the strength coefficient and strain hardening exponent to graphite fraction and graphite morphology are presented. A validation of the models presented was performed on material specimens taken from the production line at Daros Piston Rings AB. The plastic deformation of a graphite-free pearlitic matrix is discussed in Supplement VIII. The pearlitic matrix deformation data are used in Supplement V to describe correlations for different graphite fractions, covering the range 0 – 13 area %. Furthermore, Supplement VIII studies the deformation behaviour of a ferritic matrix alloyed with 2.0 wt % Si together with the thermal properties of pearlite and ferrite.

The models and correlations presented in Supplements III and V for both elastic and plastic deformation of cast irons are used in Supplement VI. Combining these correlations it is shown that the elastic-plastic deformation behaviour, in terms of stress-strain curves, is possible to forecast with good accuracy. Modelled curves for grey, compacted and ductile pearlitic cast irons are presented.

2.2 EXPERIMENTAL TECHNIQUES

Throughout this work the properties and structures of the cast iron grades studied have been determined by several different techniques. In this section the methods used are described.

Materials

The studies reported in this dissertation treat the properties of nine grades of cast iron which can be divided into two groups. The first group of materials has principally the same chemical composition but differs in nodularity. This group of materials covers graphite morphologies from flake, through compacted to spheroidal. The second group of materials is a set of flake graphite cast iron grades with different carbon equivalents. To be able to study the deformation behaviour of a graphite-free matrix, two steel grades were cast, one ferritic and one pearlitic. The chemical composition of the grades studied is...
presented in Table 1 together with the carbon equivalent and the melt denomination used in some of the supplements.

**Table 1. Chemical composition (wt %).**

<table>
<thead>
<tr>
<th>Melt</th>
<th>Iron type</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>V</th>
<th>Ti</th>
<th>Mo</th>
<th>Cu</th>
<th>Cr</th>
<th>Ni</th>
<th>S</th>
<th>Mg</th>
<th>CE *</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>D01A</td>
<td>FGI</td>
<td>3.65</td>
<td>1.92</td>
<td>0.86</td>
<td>0.08</td>
<td>0.051</td>
<td>0.008</td>
<td>0.51</td>
<td>1.09</td>
<td>0.27</td>
<td>0.37</td>
<td>0.012</td>
<td>0.001</td>
</tr>
<tr>
<td>2</td>
<td>D01B</td>
<td>CGI &lt; 10 % nod.</td>
<td>3.58</td>
<td>2.12</td>
<td>0.86</td>
<td>0.09</td>
<td>0.053</td>
<td>0.008</td>
<td>0.51</td>
<td>1.10</td>
<td>0.27</td>
<td>0.36</td>
<td>0.011</td>
<td>0.013</td>
</tr>
<tr>
<td>3</td>
<td>D01C</td>
<td>CGI ≈ 25 % nod.</td>
<td>3.54</td>
<td>2.12</td>
<td>0.87</td>
<td>0.08</td>
<td>0.051</td>
<td>0.008</td>
<td>0.51</td>
<td>1.09</td>
<td>0.27</td>
<td>0.37</td>
<td>0.010</td>
<td>0.021</td>
</tr>
<tr>
<td>4</td>
<td>D01D</td>
<td>CGI ≈ 50 % nod.</td>
<td>3.49</td>
<td>2.23</td>
<td>0.87</td>
<td>0.08</td>
<td>0.063</td>
<td>0.008</td>
<td>0.50</td>
<td>1.07</td>
<td>0.27</td>
<td>0.35</td>
<td>0.009</td>
<td>0.021</td>
</tr>
<tr>
<td>5</td>
<td>D01E</td>
<td>SGI</td>
<td>3.48</td>
<td>2.90</td>
<td>0.86</td>
<td>0.08</td>
<td>0.062</td>
<td>0.009</td>
<td>0.50</td>
<td>1.06</td>
<td>0.27</td>
<td>0.34</td>
<td>0.007</td>
<td>0.070</td>
</tr>
<tr>
<td>6</td>
<td>D01F</td>
<td>SGI</td>
<td>3.30</td>
<td>2.03</td>
<td>0.46</td>
<td>0.02</td>
<td>0.015</td>
<td>0.009</td>
<td>0.46</td>
<td>0.82</td>
<td>0.04</td>
<td>0.04</td>
<td>0.004</td>
<td>0.084</td>
</tr>
<tr>
<td>7</td>
<td>D02A</td>
<td>FGI</td>
<td>2.82</td>
<td>1.13</td>
<td>0.83</td>
<td>0.09</td>
<td>0.016</td>
<td>0.007</td>
<td>0.65</td>
<td>0.89</td>
<td>0.03</td>
<td>0.03</td>
<td>0.007</td>
<td>0.000</td>
</tr>
<tr>
<td>8</td>
<td>D02B</td>
<td>FGI</td>
<td>3.08</td>
<td>1.32</td>
<td>0.85</td>
<td>0.09</td>
<td>0.017</td>
<td>0.007</td>
<td>0.71</td>
<td>0.87</td>
<td>0.03</td>
<td>0.03</td>
<td>0.006</td>
<td>0.000</td>
</tr>
<tr>
<td>9</td>
<td>D02C</td>
<td>FGI</td>
<td>3.27</td>
<td>1.25</td>
<td>0.83</td>
<td>0.12</td>
<td>0.032</td>
<td>0.019</td>
<td>0.61</td>
<td>0.84</td>
<td>0.03</td>
<td>0.05</td>
<td>0.006</td>
<td>0.000</td>
</tr>
<tr>
<td>10</td>
<td>Pearlitic matrix</td>
<td>0.82</td>
<td>2.06</td>
<td>0.86</td>
<td>0.10</td>
<td>0.055</td>
<td>-</td>
<td>0.52</td>
<td>1.14</td>
<td>0.27</td>
<td>0.38</td>
<td>-</td>
<td>0.003</td>
<td>1.54</td>
</tr>
<tr>
<td>11</td>
<td>Ferritic matrix</td>
<td>0.08</td>
<td>1.96</td>
<td>0.10</td>
<td>0.01</td>
<td>-</td>
<td>-</td>
<td>0.01</td>
<td>0.03</td>
<td>0.02</td>
<td>0.04</td>
<td>-</td>
<td>-</td>
<td>0.74</td>
</tr>
</tbody>
</table>

*Carbon Equivalent, CE=wt % C + 1/3(wt % Si+wt % P) From each material grade a casting was made from which piston rings were machined. The piston rings studied were taken from three different locations of the casting where different cooling conditions were identified. The different cooling rates gave rise to differences in microstructure. This has been studied in the supplements and correlated to the mechanical properties of the material. The piston rings studied were denoted as: ‘ring 1’ (fine microstructure), ‘ring 7’ (coarse microstructure) ‘and ring 11’ (coarser microstructure), respectively, where the number refers to the ring order within each casting. The casting and sand mould is shown in Fig. 10.

**Figure 10. Principal sketch of the casting and sand mould. Below the feeder the outer diameter is approximately 950 mm. The thickness of the casting is 40-50 mm.**
Mechanical Tests

For the determination of the mechanical properties of the materials, tensile tests, four point bending tests and hardness tests have been used.

The tensile tests were carried out in Sintech tensile test equipment with a 100 kN load cell according to SS-EN 10 002-1. The extension of the tensile test sample was registered by a double sided extensometer with a 10 mm gauge length. The extensometer was used for the determination of the 0.2 % yield stress and the modulus of elasticity. At approximately 0.5 % elongation the extensometer was removed and the extension was registered by the movement of the crosshead. The results from the tensile tests were used throughout all of the studies described in the supplements to this thesis. Due to the lack of linear elasticity in the case of FGI the modulus of elasticity is normally determined as either a tangent modulus or a secant modulus at a certain level of stress. In this study the modulus of elasticity for the FGI grades was determined as a tangent modulus at a stress level of approximately 50 MPa. All tensile tests were performed at a crosshead displacement speed of 1 mm/min.

From the tensile test data the strain hardening exponent, \( n \), and strength coefficient, \( K \) (MPa), were determined from a log-log plot by using Eq. 3. Since a two-slope behaviour was observed for several of the material grades only the \( n \) and \( K \) values for the lower strains were determined. The values determined are valid up to at least 0.5 % true strain which corresponds to a stress of approximately 75 % of the ultimate tensile strength.

The four point bending tests were performed in MTS test equipment with a 100 kN load cell where the displacement of the sample on loading was registered as a movement of the crosshead. This experimental technique was used in the study described in Supplement IV, and the samples were segments cut from piston rings with a section of approximately 20×28 mm\(^2\). The piston ring segment was supported by two lower rolls with a separation distance of 245 mm and two upper rolls separated by a distance of 120 mm.

Microstructural Analysis

A ground and polished sample was prepared from each material grade for optical microscopic studies. A Neophot optical microscope was used and the study of the distribution of the graphite particles was determined at low magnification (25×). For the determination of the graphite fraction and the structural parameters of the graphite phase (nodularity, roundness and aspect ratio) a higher magnification was used (100×). The values of the structural parameters were determined by digital image analysis based on a minimum of 3 mm\(^2\) analysed area. The image analysis was performed by Zeiss KS300 software. To be able to distinguish between the different eutectic cells in the case of FGI and CGI grades, colour etching was used (see Supplement II). The colour etching gave the possibility to measure the width of the matrix bridges separating the graphite particles belonging to adjacent eutectic cells.

For the determination of the pearlite interlamellar spacing an Electro Scan 2020 environmental scanning electron microscope (ESEM) was used. An accelerating voltage of 20 kV and magnifications of 2000× - 10 000× were used in the ESEM analyses. A minimum value based on 70-80 measurements over 10 interlamellar spacings was determined for the pearlite interlamellar spacing. The minimum value was used since this was considered to correspond to a perpendicular spacing of the pearlite lamellae.
Chemical Analysis

Determination of the chemical composition of each material was achieved by using optical emission spectroscopy equipment ARL 3560 OES. For a higher degree of accuracy the carbon and sulphur content were analysed in an Eltra CS-800 by solid state IR absorption.

Acoustic Emission

*Acoustic emission* (AE) is generated by the rapid release of energy from a localised source within the material. The localised source might originate from, e.g., plastic deformation, crack formation or crack face rubbing. The energy pulses propagate through the material and are detected by sensors placed on the surface of the specimen. The detected pulses are converted into electrical signals and the signal information is stored and processed on a standard computer. AE frequencies are typically in the range of 150-300 kHz [39].

In the study described in Supplement IV, the acoustic emission technique was used to study and quantify the occurrence of plastic deformation during four point bending tests. From each material grade the piston rings with the coarsest and finest microstructure (‘Ring11’ and ‘Ring1’) were studied. To register the acoustic emission within the material a Physical Acoustic Corporation (PAC) sensor R15 was used having its peak resonance at 150 kHz. All AE data was acquired using PAC’s AEWIN-2 software. The AE parameters analysed were the AE amplitude (measured in dB relative to 1 mV of the sensor signal), the energy content of each AE hit and the number of AE hits. For each AE hit the time was registered. To distinguish ambient noise from the surrounding bending test equipment a threshold was set at 35 dB. The different AE parameters are indicated in Fig. 11, which shows an AE signal versus time. Based on the registered AE parameters an AE hit rate (number of AE hits/time unit) was derived which gave the plastic deformation rate in the low strain range of the tested materials. The AE hit rate showed a linear behaviour up to approximately 75 % of the ultimate tensile strength for a majority of the materials tested.

![Acoustic emission signal and some acoustic emission parameters.](image-url)

**FIGURE 11. Acoustic emission signal and some acoustic emission parameters.**
Resonance Frequency and Damping Analyzer (RFDA)

For the determination of the modulus of elasticity in Supplement VII, RFDA was used. This method gives the modulus of elasticity for a small test specimen by exciting it with a mechanical impulse resulting in a vibration. The vibration is analyzed and the resonance frequency and damping capacity of the material is determined from which the modulus of elasticity is calculated according to ASTM standard [40].
CHAPTER 3

SURVEY

CHAPTER INTRODUCTION

The following chapter discusses and summarizes the results from the performed studies. Firstly, the properties that are desired for marine diesel engine piston rings are described. Secondly, the deformation behaviour and the possibility to model and simulate this behaviour are dealt with. The elastic as well as the plastic deformation behaviour is discussed.

3.1 MATERIAL PROPERTIES OF MARINE DIESEL ENGINE PISTON RINGS (SUPPLEMENT I)

This thesis work has been carried out with a focus on the demands set on the cast iron base materials of the piston rings. Supplement I illustrates the complexity of the production of high performance piston rings. In this thesis an emphasis is placed on the mechanical properties, especially the deformation behaviour, of cast irons and therefore the issues related to coating and geometry of piston rings in Supplement I are not treated here. This section of the thesis is to be seen as an overview of the properties of cast irons used in piston rings and as an introduction to the studies presented in the thesis.

The properties of cast iron are to a great extent controlled by the morphology of the graphite phase and to some extent by the constituents of the matrix, as discussed in the introduction section of this thesis. In piston rings, high thermal conductivity is desired to decrease the loads arising from thermal expansion. The thermal loads are kept to a minimum by an effective transport of the heat from the piston ring to the cylinder liner. It is also desirable to have such mechanical properties that a piston ring with good conformability to the cylinder liner is obtained, i.e., a piston ring with a stiffness giving rise to the required sealing capacity (which, of course, also is depending on the geometry of the piston ring). The piston ring that exhibits the highest demands is the top ring of each cylinder which is subjected to the largest part of the pressure drop and maximum temperatures in excess of 200 °C during the engine operation.

To tailor the base material suitable for piston rings, a compromise is required between, e.g., thermal and mechanical properties. As seen in Fig. 12, the survey in Supplement I showed that the thermal conductivity and modulus of elasticity are inversely proportional, thereby explaining the need of a compromise between these properties since a relatively high level is demanded on both of these material parameters.
**FIGURE 12.** Modulus of elasticity versus thermal conductivity of three different cast iron grades at room temperature.

Furthermore, a comparison of three cast iron grades with different graphite morphologies showed that the modulus of elasticity is constant up to higher levels of stress for the more ductile grades (CGI and SGI) as compared to the FGI grade for which the modulus of elasticity (tangent modulus) decreases immediately upon loading, as shown in Fig. 13.

**FIGURE 13.** Idealized tangent modulus versus applied stress for pearlitic cast iron with three morphologies of the graphite phase.

The different cast iron grades shown in Figs. 12 and 13 were based on the same melt, thus having a pearlitic matrix structure and an approximately equal fraction of graphite. The graphite morphology was altered by different additions of magnesium to the liquid.
The linear elasticity of CGI and SGI grades implies a more simple calculation of stresses in the ring during operation using a constant stiffness of the ring under applied stress. The modulus of elasticity is of great importance since it partly controls the stiffness and thus the conformability of the piston ring where a higher modulus of elasticity results in an increased stiffness and decreased conformability.

As seen in Fig. 13 no linear elastic region exists for the FGI and yielding takes place immediately on loading. Plastic deformation will thus arise during mounting of the ring on the piston. This effect is important to take into account in the design work of the piston ring geometry.

The CGI material, with its intermediate thermal conductivity and modulus of elasticity is found to meet the demands of the top piston ring in a marine diesel engine and is, thus, a good compromise in the choice of piston ring material.

From this introduction to piston ring properties and the choice of piston ring material it is obvious that a good understanding of both elastic and plastic deformation behaviour is needed when designing high performance piston rings.

### 3.2 PROPERTIES OF THE CAST IRON MATRIX (SUPPLEMENT VIII)

The matrix of cast irons can be considered as steel, however with quite different alloy content. The study in Supplement VIII aimed to determine how the matrix deforms without the influence of the graphite phase and how the specific alloying levels of cast iron matrices affects its strength and deformation behaviour. For this purpose, one pearlitic and one ferritic matrix (steel) were cast at three different cooling rates. The chemical compositions of the two matrices are shown in Table 1 and correspond to Melt 10 (pearlitic) and Melt 11 (ferritic). The mechanical and thermal properties were studied and correlated to microstructural parameters. In case of the pearlitic matrix the correlated parameter was the pearlite interlamellar spacing and for the ferritic matrix it was the grain size. In this thesis the discussion of matrix properties only concerns the mechanical properties.

**Figure 14.** Influence of ferrite grain size on strength coefficient and strain hardening exponent.
It was observed that the modulus of elasticity of the pearlitic matrix was independent of pearlite interlamellar spacing. A modulus of elasticity of approximately 199 GPa was achieved. For the ferritic matrix the modulus of elasticity decreased linearly (from 198 to 172 GPa) as the grain size increased, i.e., the stiffness of the material was strongly affected by microstructural coarseness.

The strength coefficient and strain hardening exponent of both matrices decreased as the microstructure coarsened as shown in Figs. 14 and 15, even if the influence of the ferrite grain size is weak.

Thus, the strength of the matrices and their deformation behaviour are, to some extent, controlled by the ferrite grain size or the pearlite interlamellar spacing.

![Figure 15. Correlations between pearlite interlamellar spacing and strength coefficient and strain hardening exponent.](image)

According to Taleff et al. [16] the yield strength of pearlite is governed by strengthening from interlamellar spacing, pearlite colony size and alloying. The study in Supplement VIII showed that the contributions from these different strengthening mechanisms were 41 % (interlamellar spacing), 15 % (pearlite colony size) and 44 % (alloying), respectively. Compared to an unalloyed pearlitic steel (with 0.83 wt % C) the corresponding values were; 30 %, 60 % and 10 %, respectively. This shows that the relatively high alloy content in cast irons governs the strength of the matrix to large extent. The contributions from the different strengthening mechanisms are derived from the correlations presented by Taleff et al. [16].

In section 3.3 the effect of the precipitated graphite phase in a cast iron matrix is further discussed regarding the strength coefficient and strain hardening exponent.

### 3.3 THE DEFORMATION BEHAVIOUR OF CAST IRONS (SUPPLEMENTS II, III, IV, V, VIII)

It is well known that the graphite morphology influences the deformation behaviour of cast irons and as the roundness of the graphite particles increases, a higher strength is normally observed. Several studies, e.g., by Patterson et al. [41] and Shao et al. [42] describe the overall mechanical properties of various cast iron grades and how they are
affected by the graphite amount and morphology. Dividing the deformation of cast irons into an elastic and a plastic part, the elastic part of deformation is often discussed in terms of modulus of elasticity and the plastic part in terms of yield strength, ultimate tensile strength and strain at failure. The present section discusses the mechanisms that govern the modulus of elasticity and the possibility to describe the plastic deformation behaviour of cast irons by means of strength coefficient and strain hardening exponent.

In Fig. 16 the deformation behaviour at low strains for some of the materials studied in this thesis is plotted. Fig. 16 shows both a stress-strain plot (a) and the corresponding tangent modulus-stress plot (b) for each material grade.

As clearly seen in the curves in Fig. 16b the FGI grades show no linear elastic response, i.e., no horizontal part in the tangent modulus-stress plots is observed. As the morphology of the graphite changes towards a nodular shape, the horizontal part is lengthened and raised. The lengthening of the plateau indicates that a linear elastic behaviour is anticipated at higher levels of stress. The level of the plateau indicates the value of the modulus of elasticity. Fig. 16 also shows that the modulus of elasticity decreases as the carbon equivalent and graphite fraction increases and as the nodularity increases the modulus of elasticity increases.

The negative slope of the linear elastic region of the curves in Fig 16b indicates that plastic deformation takes place concurrent with the elastic deformation.

To quantify the amount of plastic deformation occurring in the different cast iron grades, acoustic emission (AE) was used as described in Supplement IV. Morgner and Heyse [43] showed that the different amplitudes of the acoustic emission correspond to the kind of strain accommodating events from which they originate, as shown in Fig. 17.
In this work the deformation at small stresses and strains was studied. At higher stresses and strains the AE measurement system was saturated by higher amplitude events originating from cracking. The saturation of the system altered the slope of the linear parameter, referred to as “AE hit rate” (corresponding to the plastic deformation rate). The linearity of the AE hit rate was observed up to a stress of around 75 % of the fracture stress for the majority of the materials tested. It was revealed that plastic deformation took place, not only in the FGI grade but also in the more ductile grades (CGI and SGI) in this low strain range. For the CGI and SGI grades this plastic deformation occurred during the seemingly linear elastic portion of the stress-strain curve. The plastic deformation rate was shown to be inversely proportional to the roundness of the graphite particles. The plastic deformation rate increased linearly as the carbon equivalent increased. These correlations are shown in Figs. 18 and 19, respectively.
In Supplement II it was concluded that in FGI grades, a more severe micro-yielding of the matrix occurred at low strain levels at the sharp graphite particles compared to the CGI grades. This is reflected in Fig. 16b as a lack of linear elasticity, i.e., no horizontal plateau, and in Fig. 18 as a decrease in AE hit rate as the roundness increases. As depicted in Fig. 19, an increasing amount of graphite (i.e., increasing carbon equivalent) also increases the rate of plastic deformation. Considering the effect of microstructure coarseness on plastic deformation of the materials depicted in Figs. 18 and 19, a finer microstructure give rise to a higher rate of plastic deformation.

**FIGURE 19. Acoustic emission activity (plastic deformation rate) versus carbon equivalent for flake graphite cast irons.**

Figs. 18 and 19 clearly show that plastic deformation occurs during the seemingly elastic deformation of any cast iron grade and that the shape and amount of the graphite strongly affect the plastic deformation rate.

Considering the deformation that occurs at higher strain and stress it was shown in Supplement II that the recoverable strain, originating from closing of opened graphite cavities seen in Fig. 5 as strain component 3, decreases as the graphite shape changes from flake to compacted. Of the total strain, the recoverable strain due to closing of the opened graphite cavities on unloading was in the order of 10 % for the FGI and 4 % for the CGI. This is shown in Fig. 20 as the difference between the ideal elastic unloading curve (dashed) and the actual unloading curve. The higher value for the FGI grade was explained by the higher localized stresses at the graphite tips that led to a higher degree of opening of graphite cavities and cracking. The formation of cracks was also revealed as high amplitude acoustic emission events where the high amplitude events appeared at lower strains in the FGI grades compared to the more ductile grades. The denominations ‘Ring 1’ and ‘Ring 11’ in Fig. 20 refer to the ring position within the casting. These piston rings have a fine and coarse microstructure, respectively. The chosen maximum stress level is the approximate yield strength of each material.
To describe the elastic deformation behaviour of cast irons the modulus of elasticity is used. The overall modulus of elasticity of cast irons is influenced by the modulus of elasticity of the graphite phase. This is not well established and, as mentioned in the introduction, it varies from 4.17 GPa to 303 GPa according to the literature. In Supplement III an effort was made to understand the influence of the graphite phase on the modulus of elasticity and how the graphite modulus of elasticity varies depending on the graphite morphology. By using the model described by Boccaccini [32] (which is discussed further in section 3.4) the graphite modulus of elasticity, $E_D$, was calculated. This was achieved by substituting all variables with experimentally known mechanical and microstructural values. It was shown that the graphite modulus of elasticity depends on the nodularity of the graphite phase as presented in Eq. (5).

$$E_D = 0.173 \cdot \text{Nodularity} + 18.9 \tag{5}$$

Eq. (5) suggests that for an FGI with 100 % nodularity the graphite modulus of elasticity is 1.6 GPa and for the SGI with 100 % nodularity 36.2 GPa, respectively. The differences are due to the anisotropy of the graphite phase and the different growth modes observed for the graphite phase. When Eq. (5) was determined, the modulus of elasticity of the matrix was set to 209 GPa, as given in the literature [5, 6]. Fukumasu et al. [9] determined the modulus of elasticity for compacted graphite by nano-indentation analyses as 23±3 GPa. This is in good agreement with the value of 18.9 GPa achieved with Eq. (5) for an ideal CGI with 0 % nodularity.

In addition to the dependence on the nodularity, the modulus of elasticity was also found to depend on the microstructure coarseness as shown in Fig. 21. Fig. 21 shows that the modulus of elasticity for the FGI grades is lowered as the mean graphite particle size decreases, in contrast to the CGI grades where the inverse relation is observed. It is also observed that, as the nodularity of the CGI grades increases, the modulus of elasticity becomes independent of the coarseness of the microstructure. The observed lower modulus of elasticity, or more correctly the tangent modulus, in the finer microstructured FGI samples was in Supplement II shown to depend on the higher amount of graphite particles available to subject the matrix to yielding in the vicinity of the graphite tips.
Another conclusion in Supplement II indicates that the overall elastic response of CGI is to a greater extent controlled by the matrix properties and less by the graphite particles which is in contrast to FGI.

The strong dependence of the modulus of elasticity of FGI as well as of CGI and SGI grades on the plastic deformation rate is shown in Supplement IV where plastic deformation was evaluated by means of acoustic emission measurements.

![Figure 21. Modulus of elasticity versus mean graphite particle size and ellipsoidal aspect ratio.](image)

As concluded in Supplement IV, plastic deformation, referred to as the AE hit rate in Figs. 22 and 23, occurred at very low strains irrespective of cast iron grade. This suggests that the elastic behaviour and thus the modulus of elasticity depends on small levels of plastic deformation, resulting in the slope of the elastic part of the stress-strain curves observed for any cast iron. Correlating the modulus of elasticity with the plastic deformation rate, as determined in the AE study (Supplement IV), linear correlations were observed as shown in Figs. 22 and 23. The curves in Fig. 22 show the materials which have approximately the same carbon equivalent but vary in nodularity while Fig. 23 shows the FGI grades with different carbon equivalents. In Fig. 23 one value has been excluded from the fitted line due to an unexplained deviation. Throughout the study in Supplement IV the results from the fine microstructured samples spread to a greater extent than the coarse structured samples. This spread might be explained by a less homogenous size distribution of the graphite particles in the fine structured compared to the coarse structured, as discussed in Supplement IV. In Figs. 22 and 23 it is seen that the plastic deformation increases as the modulus of elasticity (tangent modulus in the case of FGI) decreases. This is also what could be expected for FGI grades considering that the tangent modulus of elasticity strongly depend on the plastic deformation rate. As seen in Fig. 22 this correlation is also applicable to CGI and SGI grades which, in contrast to the FGI grades, show a seemingly true linear elasticity. Thus, the elastic modulus of CGI and SGI grades also depends on the plastic deformation rate, which in turn depends on graphite fraction and morphology.
These observations suggested that the modulus of elasticity of cast irons is governed by the plastic deformation occurring in the region of low strain and seemingly elastic deformation.

In Supplement V, the plastic deformation behaviour of the materials studied was evaluated in terms of strength coefficient and strain hardening exponent. It was observed that the plastic deformation behaviour of cast irons is strongly dependent on the morphology and amount of the graphite phase. Correlating the strain hardening exponent \((n)\) to the AE hit rate (plastic deformation rate) it was shown that the \(n\)-value can be considered as a multiplication factor of plastic deformation, i.e., a high \(n\)-value indicate that the rate of plastic deformation is high. This correlation is depicted in Fig. 24.
Furthermore, the strain hardening exponent is linearly correlated to the roundness of the graphite particles as shown in Fig. 25, i.e., the strain hardening exponent is higher in the case of flake graphite cast irons as compared to ductile irons. The correlations in Fig. 24 and 25 are in agreement with the relations between the amount of plastic deformation and roundness as shown in Fig. 18.

**Figure 25. Strain hardening exponent, n versus graphite particle roundness.**

In Figs. 26 and 27, the strain hardening exponent and the strength coefficient are correlated to the graphite fraction and carbon equivalent, respectively. The cast irons in Fig. 26 are FGI grades and SGI grades for which the carbon equivalent has been varied to achieve a variation in the fraction of precipitated graphite phase. Together with the cast iron data in Figs. 26 and 27, data for the graphite-free pearlitic matrix has been included. The graphite-free pearlitic matrix depicted in Figs. 26 and 27 corresponds to the pearlitic matrix in Table 1, Melt 10. The data for the pearlitic matrix shown in Figs. 26 and 27 is for the coarsest pearlite. These data were used since they most closely corresponded to the coarseness of the pearlitic matrix of the cast irons studied. The interlamellar spacings were 0.180 µm for the cast iron and 0.200 µm for the graphite-free matrix, respectively. The properties of the graphite-free matrices are further discussed in section 3.2. The number indicated at each data point in Figs. 26 and 27 refers to the melt number as given in Table 1.

Fig. 26 gives that the strain hardening exponent is strongly correlated to the graphite content, especially for FGI grades but also for the SGI grades. The dependence on graphite content to the strain hardening exponent is due to the increase in plastic deformation as the graphite content increases.

For FGI the strength coefficient decreases as the graphite fraction increases due to the weakening effect of the graphite phase, as illustrated in Fig. 27.
FIGURE 26. Strain hardening exponent, $n$ versus graphite fraction.

FIGURE 27. Strength coefficient versus carbon equivalent (graphite fraction).

For the CGI and SGI grades studied, no correlation for the strength coefficient was found. However, it was observed that the strength coefficient increases at an increased alloy content due to alloy strengthening of the matrix.

The experimental work in Supplement V clearly showed that the strength coefficient and the strain hardening exponent of cast irons are strongly dependent on the graphite amount and morphology as well as the alloy content.
3.4 MODELLING THE MODULUS OF ELASTICITY OF CAST IRONS (SUPPLEMENTS III, VII)

To estimate the effective modulus of elasticity of cast irons with high accuracy, a model is needed which takes into account the orientation and geometry of the graphite particles in addition to the elastic parameters of the matrix and graphite. This is fulfilled by the model described by Boccaccini [32] which is presented in Eqs. (6-8), and which is more thoroughly discussed in Supplement III.

\[
E_c = E_M \left\{ 1 - \frac{\pi}{A} \left[ 1 - \frac{1}{9 \left( 1 + \frac{1.99}{B} \left( \frac{E_M}{E_D} - 1 \right) \right)} - \frac{1}{3 \left( 1 + \frac{1.68}{B} \left( \frac{E_M}{E_D} - 1 \right) \right)} - \frac{1}{5 \left( 1 + \frac{1.04}{B} \left( \frac{E_M}{E_D} - 1 \right) \right)} \right] \right\}
\]

(6)

with

\[
A = \frac{\left( \frac{4\pi}{3c_D} \right)^{2/3} \left( \frac{z}{x} \right)^{-1/3}}{\sqrt{1 + \left( \frac{z}{x} \right)^{-2} \cos^2 \alpha_D}}
\]

(7)

and

\[
B = \left( \frac{4\pi}{3c_D} \right)^{1/3} \left( \frac{z}{x} \right)^{1/3} \sqrt{1 + \left( \frac{z}{x} \right)^{-2} \cos^2 \alpha_D}
\]

(8)

The subscripts C, D and M correspond to the composite, inclusions (i.e., the graphite phase) and matrix, respectively. The modulus of elasticity is described by \(E\) and the volume fraction of graphite inclusions is described by \(c_D\). The angle between the rotational axis of the ellipsoid, i.e., the graphite particle, and the direction of the applied stress is denominated \(\alpha_D\) and is introduced as a factor \(\cos^2 \alpha_D\) which has a value of 0.33 for statistically randomly oriented particles [32]. The ratio \(z/x\) is the relation between the length and width of the ellipsoid, referred to as ellipsoidal aspect ratio (EAR). Fig. 28 shows the unit cell with some of the model parameters. The unit cell is used in the derivation of the described model. The matrix material and included material is considered isotropic for the derived model.
Using the model with constant values for the modulus of elasticity of the matrix and graphite it was found that the average relative error between modelled and experimental values was 12.7 % calculated for all the included material grades. The values used were 8.5 GPa for the graphite phase and 209 GPa for the matrix. The value of 209 GPa for the matrix is typical for any steel-like matrix structure and the value of 8.5 GPa for the graphite is used by, e.g., Cooper *et al.* [5] and Boccaccini [32]. This relatively low agreement between experimental and modelled values was believed to be due to the variation in graphite modulus of elasticity for different graphite morphologies. The modelled values (dashed line) together with experimental values from the materials studied are shown in Fig. 29. Each material grade is represented by three data points originating from the piston rings with different microstructural scales of coarseness.

As shown in Eq. (5) in the previous section it is possible to find an $E_D$ (graphite Young’s modulus) value for any kind of cast iron grade according to its nodularity by using
Boccaccini’s model. Using this continuous function for the graphite modulus of elasticity, as calculated by Eq. (5), and implementing it into Eq. (6) the average relative error was lowered to 4.3 %. This improved accuracy of estimating the modulus of elasticity is shown in Figs. 29 and 30 where the line in Fig. 30 corresponds to a perfect fit between modelled and experimental data. The solid line in Fig. 29 shows the modelled values for a continuous graphite modulus of elasticity, i.e., correlated to nodularity according to Eq. (5) and a fixed graphite fraction of 10.1 % which is the mean graphite fraction of the samples studied.

![Graph showing modelled versus experimental values of the modulus of elasticity.](image)

**Figure 30.** Modelled values versus experimental values of the modulus of elasticity. The three points for each material grade indicate data from the three piston rings materials with differences in microstructural coarseness.

As seen in Fig. 30 and as concluded in Supplement III, the model used resulted in a higher relative error in the case of coarse microstructured, high carbon equivalent FGI grades compared to the fine microstructured FGI samples and the samples from CGI and SGI grades.

It was clearly shown in Supplement III that the modulus of elasticity of the graphite phase depends on the graphite morphology, due to the anisotropy of the hexagonal graphite structure, and that it can be described as a function of the nodularity of the graphite particles. It was also shown that the most accurate prediction of the effective modulus of elasticity for different cast iron grades was found when using the deduced function for the graphite modulus of elasticity. This treatment gave rise to a continuous function of the effective modulus of elasticity which was valid for all kinds of pearlitic cast iron grades with a very high accuracy of the predicted values. The deduced values for the graphite modulus of elasticity are in good agreement with Fukumasu et al. [9] as mentioned earlier.

In Supplement VII, the model discussed above was implemented in the casting simulation software, MAGMAsoft™. A CGI engine block was simulated and the results were
compared with an actual casting from which test specimens were machined at 39 different locations. The casting is depicted in Fig. 31. The parameters investigated were nodularity and modulus of elasticity. The modelled and simulated values of the modulus of elasticity were calculated with Eqs. (6-8).

**FIGURE 31.** Studied engine block. (By courtesy of Ford Forschungszentrum Aachen GmbH, Germany).

The average relative error for the simulated Young’s modulus was 3.1 % calculated for all of the 39 studied specimens. For the simulated nodularity values, 61 % of the specimens studied were within the range determined, although those in the simulated range were somewhat overestimated. Due to the slight overestimation of the nodularity, the calculation of Young’s modulus is also overestimated since these were based on nodularity values. It is shown in Supplement VII that it is possible to simulate Young’s modulus and the nodularity of CGI with fairly good precision. This is of importance for accurate simulations of stresses and strains.

Within the casting studied the modulus of elasticity varied from 145 to 167 GPa. The average value was 157 GPa which corresponded very well to the average value of 156 GPa for the modelled values.

An important observation is that, in view of the fact that the thermal conductivity decreases linearly as the nodularity of CGI increases [44], the temperatures will become high in sections with high nodularity since the thermal conductivity is low, and high temperature leads to high strain due to thermal expansion. The higher strains in these sections give rise to high stresses resulting from the higher modulus of elasticity. It can thus be concluded that dealing with CGI in engine components is complex since the higher strength of this group of materials is “consumed” by its lower thermal conductivity and higher Young’s modulus (resulting in higher stresses and strains) compared to FGI.

It should be pointed out that the deviations observed in Supplement VII, between experimental and modelled values for the modulus of elasticity, to some extent might be due to the use of the dynamic method (resonance frequency method) for the determination of Young’s modulus in the survey. When deriving the implemented model a static method (standard tensile test) was used for the determination of Young’s modulus. Pusch et al. [45] conclude that dynamic methods result in higher values of Young’s modulus compared to static methods and the error increases as the roundness of the graphite phase decreases. For FGI grades the deviation between the methods might be as high as 25 % while for SGI
grades the error is around 5 % \cite{45}. The difference between the static and dynamic is likely to be due to the much lower stress level that the material is subjected to in the case of the dynamic method. The measured modulus of elasticity in the dynamic method is thus closer to the Young’s modulus observed at zero stress. The modulus of elasticity (or tangent modulus for the FGI grades) in this work is determined at a stress level of 50 MPa.

### 3.5 MODELLING THE STRAIN HARDENING EXPONENT AND STRENGTH COEFFICIENT OF CAST IRONS (SUPPLEMENT V)

As shown in Figs. 25-27, the strain hardening exponent and strength coefficient are related to the microstructure of the cast iron grades studied.

To determine the plastic deformation behaviour of cast irons, a set of correlations have been established in Supplement V as given by Eqs. (9-13). Eqs. (9-12) give the value of the strain hardening exponent and were derived from the graphs shown in Figs. 25 and 26.

- **Fine (Fig. 25):**
  \[ n = -0.332 \cdot Roundness + 0.278 \]  \hspace{1cm} (9)

- **Coarse (Fig. 25):**
  \[ n = -0.397 \cdot Roundness + 0.280 \]  \hspace{1cm} (10)

- **FGI (Fig. 26):**
  \[ n = 1.63 \cdot GraphiteFraction + 0.055 \]  \hspace{1cm} (11)

- **SGI (Fig. 26):**
  \[ n = 0.298 \cdot GraphiteFraction + 0.058 \]  \hspace{1cm} (12)

Eqs. (9) and (10) are valid for a carbon equivalent close to the eutectic composition (4.3 wt %).

Strength coefficient values for pearlitic FGI grades can be calculated from Eq. (13) which is derived from Fig. 27.

\[ K = -99.6 \cdot CE + 1254 \quad (13) \]

The CGI and SGI grades show no obvious correlation for the strength coefficient. Due to this, the strength coefficient was set to 882 MPa when calculating the stress-strain data. The strength coefficient chosen is the average value for Melts 2-5. A comparison of the strength coefficient for the two SGI grades (Melts 5 and 6) showed that this decreased as the content of alloying elements decreased, i.e., the strength coefficient was lower for Melt 6 with its lower alloying content.

By determining the fraction of graphite, the roundness of the graphite phase and the carbon equivalent, the strain hardening exponent and strength coefficient can be calculated. As shown in Fig. 32 the plastic part of the stress-strain curves is determined with good accuracy for pearlitic cast irons with different graphite morphologies by using the derived correlations.
The correlations presented in Eqs. (9-13) were validated on another set of cast iron materials which included two different FGI materials, one CGI and one SGI. The models were derived from materials machined from piston rings with a 900 mm diameter. For the materials used for the validation, piston rings of smaller dimensions were also included as shown in Fig. 33. The FGI and SGI grades showed a good correlation to the deduced models. Concerning the CGI grades, a larger deviation between modelled and actual values were observed. It was concluded that further investigations of the strength coefficient for CGI grades are needed.

**FIGURE 32.** Modelled values (continuous lines) versus experimental values of stress-strain data.

**FIGURE 33.** Comparison between modelled and measured stress at 0.25 % true plastic strain for model validation.
Supplement V shows that it is possible to model the strain hardening exponent and strength coefficient for pearlitic cast irons with different graphite morphologies and obtain good correlation with experimental data.

### 3.6 MODELLING THE ELASTIC AND PLASTIC STRESS-STRAIN BEHAVIOUR OF CAST IRON (SUPPLEMENT VI)

The models presented in Supplements III and V for the determination of modulus of elasticity and plastic deformation parameters ($K$ and $n$) for different cast iron grades were used in Supplement VI. The results from the combined elastic-plastic modelling were stress-strain curves with both the elastic and the plastic response calculated with Eq. 4.

In Fig. 34 experimental and modelled true stress-strain curves for the four FGI grades studied are depicted. Fig. 35 shows the data for the CGI and SGI grades with differences in nodularity. The material numbering in Figs. 34 and 35 are according to Table 2.

In general, the modelled stress-strain curves showed a fairly good accuracy up to at least 0.5 % true strain which is the limit of validity for the models describing the plastic parameters. This strain level corresponds to a minimum of 75 % of the ultimate tensile strength of each material studied.

### Table 2. Material data.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1. FGI fine</td>
<td>7 -100</td>
<td>0,22</td>
<td>0,072</td>
<td>3,23</td>
<td>133000</td>
<td>0,172</td>
<td>0,172</td>
<td>944</td>
<td>932</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. FGI coarse</td>
<td>7 -100</td>
<td>0,22</td>
<td>0,063</td>
<td>3,23</td>
<td>140000</td>
<td>0,159</td>
<td>0,158</td>
<td>905</td>
<td>932</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. FGI fine</td>
<td>8 -100</td>
<td>0,18</td>
<td>0,084</td>
<td>3,55</td>
<td>119000</td>
<td>0,171</td>
<td>0,192</td>
<td>840</td>
<td>900</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. FGI coarse</td>
<td>8 -100</td>
<td>0,25</td>
<td>0,074</td>
<td>3,55</td>
<td>126000</td>
<td>0,162</td>
<td>0,176</td>
<td>868</td>
<td>900</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. FGI fine</td>
<td>9 -100</td>
<td>0,18</td>
<td>0,101</td>
<td>3,72</td>
<td>99000</td>
<td>0,219</td>
<td>0,220</td>
<td>922</td>
<td>883</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. FGI coarse</td>
<td>9 -100</td>
<td>0,22</td>
<td>0,086</td>
<td>3,72</td>
<td>108000</td>
<td>0,207</td>
<td>0,195</td>
<td>919</td>
<td>883</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4. FGI fine</td>
<td>1 -100</td>
<td>0,13</td>
<td>0,107</td>
<td>4,32</td>
<td>72000</td>
<td>0,252</td>
<td>0,229</td>
<td>761</td>
<td>824</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4. FGI coarse</td>
<td>1 -100</td>
<td>0,20</td>
<td>0,103</td>
<td>4,32</td>
<td>85000</td>
<td>0,233</td>
<td>0,223</td>
<td>833</td>
<td>824</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5. CGI fine</td>
<td>2 28</td>
<td>0,40</td>
<td>0,108</td>
<td>4,32</td>
<td>154000</td>
<td>0,121</td>
<td>0,145</td>
<td>927</td>
<td>882</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5. CGI coarse</td>
<td>2 8</td>
<td>0,39</td>
<td>0,127</td>
<td>4,32</td>
<td>137000</td>
<td>0,118</td>
<td>0,125</td>
<td>875</td>
<td>882</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6. CGI+nod fine</td>
<td>3 47</td>
<td>0,49</td>
<td>0,116</td>
<td>4,27</td>
<td>160000</td>
<td>0,114</td>
<td>0,115</td>
<td>952</td>
<td>882</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6. CGI+nod coarse</td>
<td>3 28</td>
<td>0,43</td>
<td>0,120</td>
<td>4,27</td>
<td>156000</td>
<td>0,104</td>
<td>0,109</td>
<td>884</td>
<td>882</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7. CGI+nod fine</td>
<td>4 59</td>
<td>0,50</td>
<td>0,112</td>
<td>4,26</td>
<td>164000</td>
<td>0,099</td>
<td>0,112</td>
<td>895</td>
<td>882</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7. CGI+nod coarse</td>
<td>4 44</td>
<td>0,43</td>
<td>0,119</td>
<td>4,26</td>
<td>162000</td>
<td>0,098</td>
<td>0,109</td>
<td>863</td>
<td>882</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8. SGI fine</td>
<td>5 89</td>
<td>0,65</td>
<td>0,111</td>
<td>4,47</td>
<td>169000</td>
<td>0,086</td>
<td>0,091</td>
<td>906</td>
<td>882</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8. SGI coarse</td>
<td>5 83</td>
<td>0,54</td>
<td>0,117</td>
<td>4,47</td>
<td>162000</td>
<td>0,072</td>
<td>0,093</td>
<td>792</td>
<td>882</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
In Table 2 the **bold** figures are considered to be the main source of the error observed in the resulting curves in Figs. 34 and 35. For some of the curves the modelling errors for the modulus of elasticity, strength coefficient and/or strain hardening exponent happen to cancel each other and the resulting curve looks better than it actually should. Studying the effect of modelling errors for the different parameters \( n, K \) and \( E \) on the resulting stress-strain curves it is concluded that \( K \) has the largest effect followed by \( n \) and \( E \). An increase of 10 % in the strength coefficient, \( K \), increases the modelled true stress at 0.5 % true strain by an approximately equal amount, while the same increase in strain hardening exponent, \( n \), and Young’s modulus, \( E \), result in a lowering of 5 % and a raising of 0.2 %, respectively.
Calculating the stresses at 0.25 % and 0.50 % true strain with the combination of elastic and plastic models used in Supplement VI, the average relative error was 4.0 % and 5.2 %, respectively.

The study in Supplement VI shows that it is possible to model the true stress-strain curve for pearlitic cast iron grades with reasonable accuracy up to at least 0.5 % true strain which corresponds to approximately 75 % of the ultimate tensile strength.
CONCLUDING REMARKS

CHAPTER INTRODUCTION
This chapter presents some important conclusions that have been drawn within the frame of this thesis.

Our understanding of the tensile deformation behaviour of cast iron has been improved by the research performed for this thesis. It is shown that the overall modulus of elasticity of cast iron is governed by the modulus of elasticity of the graphite phase and the plastic deformation taking place at low strain during the seemingly linear elastic deformation. This is the case both for FGI grades as well as for CGI and SGI grades.

In this work a model for the graphite modulus of elasticity is presented. The model relates the graphite modulus of elasticity to the morphology of the graphite in terms of nodularity. This model estimates the overall properties of the graphite phase. The modelling results in high accuracy predictions of the effective modulus of elasticity.

Plastic deformation has been studied by means of acoustic emission and is shown to strongly depend on the graphite morphology and the fraction of graphite. Plastic deformation occurs immediately at the start of loading in all grades of cast iron, and increases as the roundness of the graphite particles decreases and as the fraction of graphite increases. The strain hardening exponent is strongly correlated to the low strain plastic deformation observed. The strain hardening exponent can be described as a linear function of the graphite roundness and graphite fraction.

The strength/strength coefficient of the matrix is mainly controlled by its content of alloying elements and increases as the alloying increases. With increasing graphite fraction the overall strength is lowered due to the weakening effect of the graphite phase.

The correlations found can be used to predict the elastic and plastic deformation response to uniaxial tensile load applied to pearlitic cast iron grades at room temperature.
CHAPTER 5

FUTURE WORK

CHAPTER INTRODUCTION

In the following chapter a number of proposals for future investigations are presented.

The studies and surveys presented in this thesis treat the tensile properties of different cast iron material grades. Since a component in service is normally subjected to combinations of tensile and compressive stresses, an investigation of how the morphology of the graphite affects the compressive properties would be an interesting extension to this work.

Piston rings as well as many other engine components are subjected to dynamic stresses and this work exclusively consider static properties. This implies that a survey of the dynamic properties and the influence of the material constituents would be of further interest.

The correlations found are valuable in our efforts to estimate the resulting deformation behaviour of a cast iron component. Further implementations of the correlations into, e.g., finite element software would be a method of increasing our understanding of the deformation of cast irons by simulating the load response of a given microstructure. This simulation ought to be performed together with models that describe the thermal transport properties and its dependence on graphite morphology, since thermal transport and thermal expansion largely affect the resulting stresses and strains. This kind of simulation would be of interest especially for CGI grades since the nodularity strongly influences both mechanical and thermal properties.

When designing the experiments dealing with differences in carbon content included in this work one aim was to study the influence of primary austenite on mechanical properties. In future work a study of the materials focusing on primary austenite would further improve our understanding of the deformation behaviour of cast irons.

The materials included in this work are quite highly alloyed due to the special demands made on piston rings. Further studies of other alloying compositions are of interest to investigate how the alloying content affects the deformation behaviour and mechanical properties.

The matrix microstructure for all of the materials in this thesis work is pearlitic. In a future study the deformation behaviour of other matrices is of importance.

A study of strain rate (displacement speed) dependence would be of interest to further understand the deformation behaviour.
Apart from the mechanical properties, the thermal and tribological properties are of great importance when considering the piston ring application of cast irons. Further studies on how these properties depend on the graphite phase and matrix properties are of significant value in the design work of piston rings.

All surveys included in this thesis are performed at room temperature, but in its application environment the piston ring is subjected to significantly higher temperatures. The resulting mechanical load is dependent on thermal conductivity, thermal expansion coefficient and mechanical properties at increased temperatures. These aspects are also of interest for future studies.
INFLUENCES OF THE GRAPHITE PHASE ON ELASTIC AND PLASTIC DEFORMATION BEHAVIOUR OF CAST IRONS
REFERENCES


## APPENDED PAPERS

<table>
<thead>
<tr>
<th>Supplement</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supplement I</td>
<td>High Performance Piston Rings for Two-Stroke Marine Diesel Engines.</td>
</tr>
<tr>
<td>Supplement VI</td>
<td>Modelling the Effect of Graphite Morphology on the Deformation Behaviour of Cast Irons</td>
</tr>
<tr>
<td>Supplement VII</td>
<td>Modeling and Simulation of Elastic Properties in Cast Compacted Graphite Iron Engine Block</td>
</tr>
<tr>
<td>Supplement VIII</td>
<td>Study of the Mechanical and Thermal Properties of Pearlitic and Ferritic Cast Iron Matrices</td>
</tr>
</tbody>
</table>