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Licentiate Thesis

Residual Stresses and Fatigue of Shot Peened Cast Iron

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Fracture surface of compact graphite iron with a graphite nodule.

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Abstract

The complex geometry of cylinder head in heavy-duty diesel engine makes grey cast iron or compact graphite iron a perfect material choice due to its castability, thermal conductivity and damping capacity. To increase the efficiency of the engine, the fatigue property of the material needs to be improved. Shot peening is often used to increase the fatigue strength of components. The benefits are associated with the compressive stresses induced and with surface hardening. In this research project, these effects on grey and compact iron have been analyzed for different shot peening parameters using XRD, SEM and fatigue testing methods. The ultimate aim of the project is to increase the fatigue strength of cast irons by optimization of residual stresses.

The XRD measurements and SEM examinations revealed that the shot peening parameters including shot size and peening intensity had significant influences on the resulted residual stresses and strain hardening while changing the coverage made little difference. Also differences in the peening results between the two materials were observed, which were ascribed to an effect of the different graphite morphology. Nevertheless, a residual stress profile similar to the one general considered to improve the fatigue strength in steels could be obtained in both grey and compact iron after shot peening.

The axial fatigue testing with $R=-1$ on the grey iron showed that peening using large shot size and high peening intensity (heavy shot peening) resulted in a fatigue strength reduction of 15-20% in comparison with the mechanically polished surface. The negative effects are likely related to surface damage and relatively high tensile residual stresses in subsurface induced by the heavy peening. Grey cast iron has low ductility in tension and therefore tensile residual stresses may promote multiple cracking and crack networking during cyclic loading.

Shot peening using much smaller shots and lower intensity (gentle shot peening) which resulted in a much smaller residual stress field gave no significant changes in fatigue strength. However, a short time annealing at 285°C of specimens being gently shot peened increased the fatigue strength roughly by 10%. The improvement could be an effect of precipitates formed due to the heat treatment, which lock the dislocation movement under cyclic loading.

List of Papers

The thesis is based on the following papers:

- I. M. Lundberg, R.L. Peng, M. Ahmad, D. Bäckström, T. Vuoristo, S. Johansson, "Residual Stresses in Shot Peened Grey and Compact Iron", *Accepted for publication in HTM Journal of Heat Treatment and Materials*.
- II. M. Lundberg, R.L. Peng, M. Ahmad, D. Bäckström, T. Vuoristo, S. Johansson, "Shot Peening Induced Plastic Deformation in Cast Iron – Influence of Graphite Morphology", *Accepted for publication in HTM Journal of Heat Treatment and Materials*.
- III. M. Lundberg, M. Calmunger, R.L. Peng, "In-situ SEM/EBSD Study of Deformation and Fracture Behaviour of Flake Cast Iron", *Presented at the 13th International Conference on Fracture, Beijing, China, June 16-21, 2013*.
- IV. M. Lundberg, R.L. Peng, M. Ahmad, D. Bäckström, T. Vuoristo, S. Johansson, "Fatigue Strength of Machined and Shot Peened Grey Cast Iron", *Accepted for publication in Advanced Material Research. To be presented at Fatigue2014*.

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Nomenclature

EBSD	Electron Back Scattering Diffraction
ECCI	Electron Contrast Channelling Imaging
SPZ	Severe Plastic Zone
LAGB	Low Angle Grain Boundary
HAGB	High Angle Grain Boundary
UTS	Ultimate Tensile Strength
SEM	Scanning Electron Microscope
XRD	X-ray Diffraction

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Part I:

Theory and background

1. Introduction

First I want to thank you as a reader for having this thesis in your hands. When you start to read you will most certainly find much interesting information about cast iron.

Part I in this thesis is intended to provide you with proper background and theory of the project and what has been done, and in the end the conclusions of the work done so far.

Part II consists of four scientific papers, two journal articles and two conference proceedings.

1.1. Background

This licentiate thesis is a part of the project *FFI-Increased fatigue strength of cast iron components through optimization of residual stresses* which started during the winter 2010/2011. The project is financed by VINNOVA and is executed in a strong collaboration with Scania CV AB and Volvo Powertrain.

Cast irons are state-of-the-art material for cylinder heads in heavy-duty diesel engines and with the increasing demands on fuel efficiency and lower emissions something needs to be done to meet the criteria. To meet the criteria one can either change material or optimize the one already in use. Residual stresses can be detrimental or beneficial for a component depending on load case and sign of the residual stresses. To optimize the residual stresses at critical locations in the component should make it possible to increase the diesel engine working pressure, thus coming closer to fulfil the demands on fuel economy. Since the environmental laws are getting tougher by the year, the manufacturer needs to stay in front of the regulations and provide the customer with goods, fulfilling the emission laws. For truck manufacturer like Scania and Volvo, the increasing demands on the engine fuel efficient and low CO₂-emission soon reaches the upper limit for the material used today. To meet this problem one can either change material, which is not practical without massive investments and investigations, or one can get better material knowledge in order to improve the properties of the already existing material or components.

1.2. Relevance of research project

As the combustion pressure of heavy truck engines increases due to higher demands on engine power, fuel economy and emissions, the load on the cylinder heads increases. The loading that cylinder heads are subjected to varies cyclically, but also a varying thermal load is applied. To meet the increasing requirements, the fatigue strength of the material use today needs to be improved. One possible solution to meet these higher demands could be to optimize the residual stress state of the cylinder heads. Cylinder head is only one example of a component whose loading is directly affected by the increasing demands, thus the obtained results might be applicable to other components. Through optimization of residual stresses the fatigue strength of cast iron components may be markedly improved. Increased fatigue strength of the material could also enable weight reduction of the components as thinner walls should be possible through residual stress optimization. The improved material property, the fatigue strength, will promote in meeting the constantly increasing demands on the diesel engine. With better understanding of the correlations between manufacturing methods, residuals stresses and fatigue strength will provide the companies an advantage in designing new and durable components.

Cylinder heads for heavy truck applications are mainly produced of grey iron. Grey iron exhibits a number of positive physical properties such as high thermal conductivity and high damping capacity. The complexity of the products also limits the selection of materials and manufacturing methods. The downside of using grey iron is the relatively low fatigue strength. Several researchers have increased the fatigue strength on different components through shot peening. When doing so the shots will introduce compressive residual stresses at the surface and this is generally beneficial for the fatigue strength. However, the effects from shot peening and the induced compressive residual stress field on cast iron, especially grey cast iron, has not yet been studied thoroughly . Tailoring the residual stresses at critical locations would offer a cost effective alternative to increase the fatigue performance of the component meeting the ever increasing requirements on the engine performance.

1.3. Research aims

The financier VINNOVA, which is a Swedish Governmental Agency of Innovation Systems, has the global goal *“to strengthening Sweden’s innovativeness, aiding sustainable growth and benefiting society”*.

In VINNOVA there is a program called “Strategic Vehicle Research and Innovation” and within this program there are four areas of research interests. The vision of the program area where this project belongs to is to *“Provide the vehicle industry with innovative materials and access to new state-of-art material usage”*.

The research aim of this project is to *“understand and control the residual stress field of cast iron components to increase the components fatigue life”*. To be able to achieve this, the research work focused on the following aspects:

“Development of fast and reliable residual stress measurement techniques”

“Prediction of residual stress field from surface treatments, i.e. machining, shot peening, etc.”

“Understanding the residual stress field importance on the fatigue life in cast irons”

Within the scope of this licentiate thesis, the research done (and on-going) is mainly dedicated to the understanding of the residual stresses and material deformation induced through shot peening, and the link between this and fatigue response in grey cast iron in axial fatigue.

2. Cast Iron

The term *cast iron* identifies a large group of ferrous alloys that solidify with an eutectic, in contrast to steels which solidify with an eutectoid. Cast iron consists of many elements, among which iron, carbon and silicon are the major elements. When talking about cast iron and their properties, one should mention the most important factors affecting the outcome: the chemical composition, cooling rate, liquid treatment and heat treatment. Furthermore, the third major element in cast iron (silicon) affects the graphite, the pearlite and solvus temperature. Thus the amount of silicon needs to be considered when casting a component [1,2].

Still in the beginning of 19th century cast iron was divided into two different groups, based on the colour on the fracture surface, grey cast iron or white cast iron. As the light optical microscope evolved, the scientists started to investigate the material and found that the shape of the graphite could vary a lot, still giving the same grey fracture surface. More classifications were needed and the shape of the graphite have since then been used to classify the cast iron. As the metallurgy was breaking new grounds, different amounts of alloying elements and their effects on the mechanical properties were investigated and in the end this led to a more narrow classification of cast iron. The latest European Standard deals with the cast iron classifications using letters, describing the graphite shape and followed by three numbers, defining the ultimate tensile strength. For example, GJS-500 and GJL-300 stands a for spherical cast iron with an ultimate tensile strength of 500 MPa and a lamellar cast iron with an ultimate tensile strength of 300 MPa, respectively.

2.1. Graphite and matrix

In Figure 1 below the most typical shapes of graphite according to ASTM A 247 standard are shown. These are the primary shapes of graphite in cast iron and once the shape is identified the next step is to analyse the dimensions and the distribution of the graphite, following the standard.

Figure 1: Typical shapes of graphite from ASTM A 247 standard. I) spheroidal graphite, II) imperfect spheroidal graphite, III) temper graphite, IV) compacted graphite, V) crab graphite, VI) exploded graphite, VII) flake graphite.

In the classification of grey cast iron it is important as a foundry to be able to specify, not only, the mechanical properties of the cast component, but also, the graphite flake size, especially for grey cast iron. The foundry should mention the graphite flake size, according to a standard, in the cast component. In the standard EN ISO 945:1994 the flake sizes are divided into eight different categories based on the longest flake size, expanding from the longest flakes of 100 mm or more down to the smallest category of flake size of less than 1.5 mm in size, see Figure 2. The flake size refers to the perceived size in x100 magnification, thus the actual flake size is 100 times smaller.

Figure 2: Graphite shapes in grey cast iron according to EN ISO 945:1994

Large flake size is associated with slow cooling rates in irons having high carbon equivalent values. The attributed changes in properties of grey cast iron consisting of large flake sizes are high thermal conductivity and damping capacity on the cost of strength. Hypoeutectic iron subjected to rapid cooling (not quenching) generally provides very small flake sizes, which results in a high tensile strength since the short graphite flakes interrupt the matrix to a smaller extent. Finally we have come to the category of graphite distributions according to ASTM A 247 and ISO 945:1994 as can be seen in Figure 3.

Figure 3: Graphite distribution in grey cast iron according to ASTM and ISO. Type A Random flake graphite in a uniform distribution. Type B Rosette flake graphite. Type C Kish graphite (hyper-eutectic compositions). Type D Undercooled flake graphite. Type E Interdendritic flake graphite (hypo-eutectic compositions).

Depending on the graphite morphology different mechanical properties can be achieved with the same type of matrix. For example, a pearlitic flake cast iron with a nominal flake length of 150 μm has much better damping qualities and lower tensile strength than a pearlitic flake cast iron with a nominal flake length of 20 μm .

In cast iron the matrix is one of the following: ferritic, pearlitic, austenitic, martensitic or bainitic (often called austempered). The most common matrix in cast iron castings is ferrite or ferrite-pearlite. Ferrite is the soft low-carbon $\alpha\text{-Fe}$ phase that has low tensile strength but excellent ductility. Ferrite is often found in conjunction with undercooling. Pearlite is the eutectoid transformation where the

austenite transforms to a lamellar structure of ferrite and cementite. The hardness and tensile strength of pearlite are higher than in ferrite but with lower ductility. With a smaller lamellar spacing in the material, the hardness and tensile strength increases. The lamellar spacing and thus the mechanical properties can be controlled with a more rapid cooling or alloying elements. The cementite phase in pearlite is an intermetallic compound ($\text{Fe}_3\text{-C}$) and is very hard and brittle. As a comparison of these microconstituents, an increase in hardness from 75 to 200 to 550 HB for the ferrite, pearlite and cementite respectively are accepted as standard values. Tensile strength and elongation of ferrite are roughly 280 MPa and 60 % respectively whereas the pearlite possesses a tensile strength up to 860 MPa and 10 % elongation.

3. Residual stresses

The term *residual stress* used by engineers is related to local variations in strains inside the material on a macroscopic or microscopic level without any external load acting on the material. They arise from elastic response to an inhomogeneous distribution of non-elastic strains. The most common sources of non-elastic strains, and thus residual stresses, are plastic deformation, phase incompatibility and thermal expansion strains. The strain variations can be converted into stresses which are fundamentally easier to grasp and defined as the force per square meter. The “conversion parameter” differs between the materials due to their different response to loading [3,4].

3.1. XRD measurements of residual stresses

Residual stresses in a work piece can be divided into macro- and microstresses [3-5]. By definition the *macrostresses* are the same in all phases present at the same depth in the material. Consider the plastic deformation occurring at the surface during machining operations where the deformation of the surface layer will be constrained by the bulk where the plastic deformation is minimal, if existing. Macro stresses are self-equilibrated through the cross-section of the work piece. In multi-phase materials the differences in yield point and possible response to mechanical load results in inhomogeneous strains in the material volume. Strong phases constraining the weaker ones and giving rise to stresses on a microscale level, these are the *microstresses*.

Cast residual stresses are present in the as-cast condition in all castings due to differences in cooling rates in different parts of the component during solidification, strength of the mould and cleaning of the cast work piece. The main contributors to residual stresses that one needs to keep in mind when casting are the different cooling rates in the work piece and the blast cleaning, or rather the energy of the blast cleaning process. When casting complex geometries, the wall thickness often differs much and this does not only affects the thermal residual stresses but also the microstructure in the final component. When casting a component in grey cast iron, a sand mould is commonly used. To get rid of the sand residues, sand blast cleaning is often applied and depending on the energy output of the blasting medium, considerable amount of residual stresses can be introduced at the surface.

The force associated with stresses in material are not measured, instead the strain(s) are measured and later converted to stresses by different methods depending on stress measurement used. Perhaps a more correct phrase is to say that we measure changes in strains by some means, which are related to stresses.

Let's continue with an introduction to basic residual stress measurements with x-rays. To do so firstly we need to state the origin of the Cartesian coordinate systems used; the specimen (S) and the laboratory (L) system, see Figure 4. Once the constitutive equations that describe the two coordinate systems are expressed we can apply these to the method used in this project to measure the residual stresses with x-rays.

Figure 4: Coordinate systems used in stress measurement with x-ray diffraction

The stresses (and strains) are defined in the specimen coordinate system and L_3 direction is the bisectrix between the incoming and the diffracted x-ray beam, defined by the two angles ψ and ϕ . From this relation we can derive the strain equation from the sample coordinates to our laboratory system, or vice versa. The calculated stresses and strains will be expressed in the sample coordinate system. By tensor transformation we can then write the normal strains in the sample expressed from strains obtain in L_3 as [4,6,7]:

$$\begin{aligned} \epsilon_{\phi\psi} = \frac{d_{\phi\psi} - d_0}{d_0} = & \epsilon_{11} \cos^2 \phi \sin^2 \psi + \epsilon_{22} \sin^2 \phi \sin^2 \psi + \epsilon_{33} \cos^2 \psi \\ & + \epsilon_{12} \sin 2\phi \sin^2 \psi + \epsilon_{13} \cos \phi \sin 2\psi + \epsilon_{23} \sin \phi \sin 2\psi \end{aligned} \quad \text{Equation 1}$$

The relationship between strain and stress for an isotropic material is given by Hook's law as:

$$\varepsilon_{ij} = \frac{1+\nu}{E} \sigma_{ij} - \frac{\nu}{E} \delta_{ij} (\sigma_{11} + \sigma_{22} + \sigma_{33}) \quad \text{Equation 2}$$

Where δ_{ij} is the Kronecker delta function:

$$\delta_{ij} = \begin{cases} 1 & \text{if } i = j \\ 0 & \text{if } i \neq j \end{cases} \quad \text{Equation 3}$$

This holds, as mentioned earlier, for an isotropic material if ε_{ij} is homogeneous within the penetration depth of the x-rays.

The combination of Equation 1 and 2 results in the general working equation for X-ray stress analysis:

$$\begin{aligned} \frac{d_{\phi\psi} - d_0}{d_0} = & \frac{1+\nu}{E} (\sigma_{11} \cos^2 \phi + \sigma_{12} \sin 2\phi + \sigma_{22} \sin^2 \phi - \sigma_{33}) \sin^2 \psi \\ & + \frac{1+\nu}{E} \sigma_{33} - \frac{\nu}{E} (\sigma_{11} + \sigma_{22} + \sigma_{33}) \\ & + \frac{1+\nu}{E} (\sigma_{13} \cos \phi + \sigma_{23} \sin \phi) \sin 2\psi \end{aligned} \quad \text{Equation 4}$$

With this stress measurement technique, the crystal lattice is used as an internal strain gauge. By comparing the stressed lattice spacing ($d_{\phi\psi}$) with the unstressed lattice spacing (d_0), then the strain can be calculated according to:

$$\varepsilon_{\phi\psi} = \frac{d_{\phi\psi} - d_0}{d_0} \quad \text{Equation 5}$$

When a monochromatic x-ray beam irradiates the material, some of the photons that irradiate the surface will scatter back due to phenomenon called diffraction and finally some will hit the detector. The amount (counts) of photons detected will later be plotted as a function of diffraction angle. Due to the crystal planes in the material and its regularity of atoms in crystalline materials, the scattered waves lead to interference (diffraction) when Bragg's law is fulfilled:

$$2d_{hkl} \sin \theta_{hkl} = n\lambda \quad \text{Equation 6}$$

Where d_{hkl} is the lattice spacing of the diffracting plane, θ is the angle between the diffracted plane and the incident beam; λ is the x-ray wavelength generated from the tube and n is an integer set to be 1 on x-ray analysis. In Figure 5, a schematic representation of un-stresses and stressed crystal planes satisfying Bragg's law is shown.

Figure 5: Different lattice spacing gives different diffracting angles if Bragg's law is fulfilled

3.2. The $\sin^2\psi$ -method

The most common method to measure residual stresses from diffraction data is the $\sin^2\psi$ -method and usage of biaxial stress state. Biaxial (plane) stress state means that the data obtained is not affected by strains in the normal direction (out of the specimen). Due to the shallow penetration depth of the x-rays, in the order of 5-50 μm depending on the material and source of x-rays [3], this is a fairly good assumption to use and it does make the evaluation of residual stresses measured with this method much easier.

Next assumption needed to make it possible to measure stresses with this technique is that the lattice spacing normal to the surface is the same as the material parameter d_0 for the diffracted plane when $\psi = 0^\circ$.

In practise, several measurements are made in different ψ -angles at specific ϕ -angle and with the assumption made Equation 6 reduces to

$$\varepsilon_{\phi\psi} = \frac{d_{\phi\psi} - d_0}{d_0} = \frac{1+\nu}{E} \sigma_{\phi} \sin^2 \psi - \frac{\nu}{E} (\sigma_{11} + \sigma_{22}) \quad \text{Equation 7}$$

since we assume biaxial stress state. The surface stress component (σ_{ϕ}) is given to be (recall Equation 4):

$$\sigma_{\phi} = (\sigma_{11} \cos^2 \phi + \sigma_{12} \sin 2\phi + \sigma_{22} \sin^2 \phi) \quad \text{Equation 8}$$

The $\sin^2\psi$ -method has the advantage of making it possible to measure the stresses in the sample without knowing the unstressed lattice spacing (d_0), as mentioned earlier. This leads to faster measurements.

When $\psi=0$ then equation 4 reduces to only the last component:

$$\varepsilon_{\phi 0} = \frac{d_{\perp} - d_0}{d_0} = -\frac{\nu}{E} (\sigma_{11} + \sigma_{22}) \quad \text{Equation 9}$$

Here $d_{\perp}$ denotes the lattice spacing parallel to the specimen surface normal. Then by using equation 9 in 7 we rewrite it and that results in

$$\frac{d_{\phi\psi} - d_{\perp}}{d_0} = \frac{1+\nu}{E} \sigma_{\phi} \sin^2 \psi \quad \text{Equation 10}$$

Now $d_{\perp} \approx d_0$ and the error is negligible [6] which allows us to replace d_0 in equation 10 with $d_{\perp}$ resulting in the final equation used in this method

$$\frac{d_{\phi\psi} - d_{\perp}}{d_{\perp}} = \frac{1+\nu}{E} \sigma_{\phi} \sin^2 \psi \quad \text{Equation 11}$$

Thanks to this equation we easily see the linear dependency of the measured lattice spacing and $\sin^2 \psi$. When plotting the lattice spacing against $\sin^2 \psi$, the slope of that line contains the surface stresses measured.

Mechanical polished compact graphite iron

Figure 6: Data used to calculate residual stresses using $\sin^2 \psi$ method.

By dividing the slope m with $\frac{1+\nu}{E}$ the component σ_{ϕ} can be solved and thus we have obtained a value of the surface residual stress.

The terms $-\frac{\nu}{E}$ and $\frac{1+\nu}{E}$ (see Equation 7) relate the macroscopic elastic data with the residual stresses measured with x-rays. They are both important in x-ray analysis and commonly called the x-ray elastic constants (XEC:s), s_1 and $\frac{1}{2}s_2$ respectively. Since the Young's modulus depends on crystallographic plane studied, a more correct notation would then actually be:

$$-\frac{\nu}{E_{(hkl)}} = s_{1(hkl)}$$

$$\frac{1+\nu}{E_{(hkl)}} = \frac{1}{2} s_{2(hkl)}$$

Thus the x-ray elastic constants show the importance of knowing which diffraction plane used in the measurement [4,8]. Observe that when using $\sin^2\psi$ method, only $\frac{1}{2}S_2$ is needed for the stress measurement. The XEC value used will affect the residual stress results obtained and when analysing stresses in a complex multiphase material it all becomes little elusive and one must carefully examine the stresses. When an absolute residual stress value is very important, in critical components for instance, determination of XEC needs to be done by experiments on the actual material used with all of its alloys. By adding alloying elements the lattice spacing might be affected due to solid solution and thus the response to loading.

Peak broadening.

The diffraction peak obtained will have some width and this width can provide the researcher with useful information about the studied material, if interpreted correctly. Peak broadening occurs in a stressed material partly due to inhomogeneous strain distribution in the probed volume and partly from the beam divergence. In this project we have made use of this by studying the changes in peak widths as the stressed material is removed and the amount of inhomogeneous strains is diminished. The peak width at half the height of the peak (after subtraction of background noise) is calculated and referred to as the Full Width at Half Maximum (FWHM). FWHM-values provide the researcher with qualitative data on the degree of plastic deformation in the probed volume, if the same instrumental setup is used the same way every time [3,5]. Between the measurements one can remove some of the material by electrolytic polishing. This can be done in the scale of 5-10 microns to a few hundreds of microns and by doing so, both the residual stress profile and the FWHM profile can be obtained. These profiles provide the researcher with much information concerning the residual stress distribution and the amount of work hardening at the surface.

Non-linear “d vs $\sin^2\psi$ ” curves.

The curve seen in Figure 6 is very linear and the least square fit results in a 98,8 % linear fitting which is very good. Imagine instead that you have a splitting of the curves as can be seen in Figure 7, having a linear fitting of only 42,8 %. Then the question ought to be: “Why do we have this splitting?”

Figure 7: Splitting of d vs $\sin^2\psi$ curves

With the assumptions earlier made (recall Equation 11), we state a biaxial stress state. This is not always the reality that we have a biaxial stress state and an example of this can be after turning. The shearing of the material when machining or turning can result in curve splitting as seen in Figure 7. This is an effect of existing σ_{13} and σ_{23} stresses that may be finite and exist as gradients in the probed volume. To assure that the curve splitting is not an effect of anything else one can rotate the sample 180° and do the measurement again. This should result in exactly the same plot but with the d-spacing calculated from the negative psi-angles now being the values calculated from the positive angles. Thus the d-spacing from the positive psi-angles after rotating 180° should be the same as the one calculated from the negative psi-angles before rotating.

4. Fatigue

The word *fatigue* used in engineering has become widely accepted for the damage and failure of materials under cyclic loading. In a report from 1964 the International Organization for Standardization defined the term fatigue as “applied to changes in properties which can occur in a metallic material due to repeated application of stresses or strains, although usually this term applies specially to those changes which lead to cracking or failure”. This description is generally also valid for non-metallic materials. “Fatigue” can be used in various fields of research and having different insinuations. In engineering it is often used together with a “prefix” or a “suffix”, e.g., fluctuations in externally applied stress or strains result in *mechanical fatigue*. At high temperature the pre-mentioned situation sets the usage of *creep-fatigue*. When both the temperature and the external load vary the term *thermomechanical fatigue* is needed. Also the scientific community deals with *sliding contact fatigue*, *rolling contact fatigue*, *corrosion fatigue* and *fretting fatigue* [9]

The work done by Wöhler in 1860 on rotary bending of railway axel for the Prussian Railway lead to the characterization of fatigue behaviour, still in use and well accepted, in terms of stress amplitude-life (S-N) curves. From his work the concept of fatigue endurance limit was firstly stated, probably due to some testing performed that was subjected to 132 250 000 cycles without failure. For the interested person it is worth mentioning that Wöhler’s testing machine had a maximum speed of 72 revolutions per minute [10].

Fatigue testing done within the scope of this thesis refers to *mechanical fatigue* mentioned above. For this type of testing, the fatigue mechanisms observed by Ewing and Humfrey [11] in the very beginning of the 20th century, slip bands developed during cyclic loading in many grains in the polycrystalline material studied. They saw that these slip bands became broader as the cyclic loading continued and later resulting in formation of cracks. The catastrophic failure was a result of the growth by a single dominant crack. They could also see that slip bands cause slip steps in the form we now call “extrusions” or “intrusions” when the slip bands penetrate the surface. From this formation of slip steps at the surface of the specimen, the fatigue crack starts.

4.1. Fatigue of cast iron

From the 60's to the mid 80's much work was done on characterizing the mechanical fatigue behaviour of grey cast irons. The kind of fatigue tests performed during almost 30 years were bending and rotary bending fatigue and fairly much effort was put to explain the deformation behaviour in grey cast iron [1,2]. Empirical models predicting the total fatigue life have been proposed during the years of fatigue studies. Different research groups have proposed different deformation mechanisms occurring in grey cast iron under tensile and cyclic loading [12-17]. Deformation mechanisms stated have its pros and cons when modelling the fatigue behaviour of the material. Nevertheless, the models proposed had a fairly good agreement with the tests performed in the low-cycle-fatigue regime.

When searching the literature it is evident that grey cast iron lost the researchers' interest during the 80's whereas the amount of publications concerning nodular cast iron has remained constant. The number of publications dealing with fatigue behaviour has always been a relatively small part of the published articles. Much attention has been paid on understanding the solidification process and building of models predicting the mechanical behaviour of the cast component of nodular cast iron. The link between different surface conditions and their effects on the fatigue strength under various types of loading has not gained proper attention from the scientific community until the last 5 years. However, publications on surface effects on the fatigue properties of nodular cast irons can be found [18].

In grey cast iron the crack initiation period can be set to zero % of the fatigue life which should be compared to the 90 % of the fatigue life proposed in steel [9,10]. Due to the very poor tensile strength of graphite the deformation starts directly during the first loading cycle if the fatigue test involves tensile loads. The graphite oriented perpendicular to the loading direction opens at stresses between 0 and 55 MPa, depending on matrix strength [12]. The opening of the graphite then results in a diminished stiffness upon the next loading, which can be treated as the load-bearing area has decreased. As a consequence of this, micro-cracking and/or crack networking occurs in the material. Fash and Socie [17] concluded in their fully reversed axial fatigue testing that micro cracking and crack networking started during the first cycle at the surface and continued to grow to a size of 1-2 mm. Worth remarking here is also that the dimension on the test specimen was 10 mm in diameter having a gauge length of 28 mm. They acquired the crack growth data by taking several series of replicas during fatigue testing.

Cast iron is often considered to have low notch sensitivity due to all the voids (graphite inclusions) present in the material. In tensile loading the graphite is very

weak and tends to slip at loads in the order of 40 MPa [12,19]. On this basis the graphite in grey cast iron can be treated as pre-existing cracks or voids when loaded in tension. On the other hand the graphite can carry much larger loads in compression, which is the main factor for the asymmetric tension/compression curve for grey cast iron, see Figure 8.

Figure 8: Tension/compression asymmetry normally found in grey cast iron [20]

Current practice in design criteria of grey cast iron is to use 25-35% of UTS as maximum cyclic tensile stress. The work done by Willidal et al [21] showed that using 0.07% strain was a better indicator for the fatigue limit than the current praxis in the beginning of 21th century. From their axial fatigue testing with $R=-1$ on different grades of grey cast iron they found out that all run-out samples had been subjected to a strain level of 0.07% with an accuracy of 5%.

Both materials studied in this project have a relatively low tensile strength: 300 MPa for the grey cast iron and 400 MPa for the compact graphite iron. Nevertheless it is the state-of-art material for this application and reasons why it is still in use is the price, the thermal conductivity and damping capacity. The cost for each cylinder head manufactured depends not only on the direct casting cost but also on the post treatment needed to obtain the correct dimensions. With cast iron it is possible to cast very complex geometries to final dimensions and the material is easy to machine. On the negative side, this material has a low fatigue strength, as discussed above, when comparing steels with the same tensile strength. Also one needs to have in mind the different cooling rates and the complex geometry result in different properties in different locations of the component.

4.2. Residual stress effects on fatigue

It is commonly known that when applying tensile loads on a component, the surface will be most sensitive for crack initiation due to the lack of constraining material at

the surface. By introducing compressive residual stresses in a thin surface layer, fatigue crack initiation period will be enlarged. On the other hand, tensile residual stresses at the surface shorten the time to crack initiation.

In a survey on the influence of residual stress distributions on fatigue life by Webster and Ezeilo [22] it is obvious that residual stresses can be detrimental or beneficial for the fatigue life. An example when tensile stresses are likely to be present in critical components is after welding. Two cold work pieces are attached to each others by the melted material and are cooled after welding. The large differences in temperatures result in tensile residual stresses at the weld. Welds in aluminium alloys that have been further treated, resulting in compressive residual stresses at the weld, had a typical increase in fatigue life with 60 % [6].

There are several different ways of introducing compressive residual stresses at the component surface [23]. In 1966 Porokhov and Bogachev [24] showed on a medium carbon steel that depending on the mechanical surface strengthening method used an increase in fatigue life between 20 and 50 % was expected. The surface treatments resulted in slightly different residual stress distributions which to some extent can be compared to the change in the fatigue life, more compressive stresses leading to increased fatigue life.

Different surface finishing and different machining methods also result in residual stresses at the surface. Normally the residual stresses are compressive, but they can be tensile with inadequate turning parameters, and have been shown to strongly influence the fatigue limit in steels [25-29]. Gentle grinding can result in very high compressive surface stresses that normally drop very quickly with increasing depth and approach zero after 40 to 80 μm , giving an increased fatigue life of 20 to 25 %.

Ghanem et al [30] investigated the residual stress distribution after electro-discharge machining (EDM) in a tool steel and its effects on the fatigue life. The test piece was subjected to three-point bending and the fatigue limit was defined at 10^6 cycles. Tensile residual stresses from EDM resulted in a decrease of 35 % compared to the reference process (milling).

Laser treatment is an effective procedure to induce residual stresses and Belló et al [25] investigated the effects in 50CrV4 steel. Besides the importance of coverage they found a 40 % increase in fatigue life due to the residual stress distribution and the microstructural changes of the surface layer.

So far, the discussion has mainly focused on the fatigue limit enhancement as a consequence of compressive residual stresses. Before closing this chapter I would

like to point out one thing; the effect of the induced compressive residual stresses on the fatigue life in low-cycle-regime is not as clear as it is on the fatigue limit.

5. Shot peening

Shot peening is a cold work process involving small spherical shots bombarding a surface [23]. During the impact some of the kinetic energy of the shot will be transmitted to the surface. This will result in a small indentation and as a consequence local yielding of the material occurs, leaving compressive residual stresses at the surface. In theory, the media used for shot peening can be almost anything as long as the shape and size of the media can be proclaimed but in practise there are a few standards to follow. There are a few different types of machines used to shoot the spherical shots on the target, each with its own benefits. When shot peening a component there are a few parameters considered to be critical for the out-come of the process. The parameters are peening intensity, coverage, duration, impact angle and peening media quality.

Figure 9: Illustration showing how compressive residual stresses are induced upon the cold work by the shot peening process. ©Metal Improvement Company

Shot peening effects on fatigue strength of steels, titanium and superalloys.

At the end on the Second World War, it was commonly accepted and proven that surface residual stresses can be beneficial or detrimental to the tensile fatigue life. Now many researchers started to investigate how much residual stresses can be introduced to the surface and to what depth by means of shot peening. Mainly their research was conducted on various spring steels and their pioneering work showed that the kinetic energy transferred played an important role on the fatigue life. Coombs et al [31] made an attempt to measure the most effective peening affected depth for several different shot peening conditions. To find this depth they removed some material of the specimens and then determined the fatigue life. What they found was at a certain depth (when some material had been removed)

the maximum cycles to failure were found for all the test conditions. Their explanation to this phenomenon was that at a certain depth below the shot peened surface, there exists a maximum compressive residual stress peak.

Today it is considered that shot peened steels have a maximum compressive stress peak just below the peened surface. By screening the literature dealing with shot peening of different steels and its effects on different loadings [23,26-29,32-41] it becomes clear that shot peening is a very effective and cost efficient post treatment to increase the fatigue strength of steels. To find the optimum shot peening conditions for the steel might be impossible without narrowing down the problem to a specific steel under specific loadings [42].

Other materials that during the years have been shot peened successively and obtained increased fatigue strength are titanium, aluminium and superalloys [43-51]. Also some brittle materials [52-54], like ceramics, which have been shot peened with proper shot peening parameters, have shown an increase in fatigue strength.

Shot peening of cast iron.

One ought to think for a material like cast iron that is so widely used for so many years (over 2000 years), everything has already been done. Probably this is true, but a lot of work on cast iron has been done by companies and the results have not become public. Thus there exists a gap in knowledge in the scientific community today about cast irons. During the last 15 years of research on cast iron, the main area of interest has been in the solidification process and how to affect it to get the best mechanical properties (static). Surprisingly few articles discuss how the fatigue properties vary under different loading for the different cast irons available today. Even fewer articles are found in the topic of shot peening of cast iron. Most of the articles deliberate a nodular cast iron with various microstructures under different peening conditions [55-61]. One of the earliest publications concerning shot peening and cast iron, showed that the benefits of shot peening on the fatigue life of nodular casting [62] is three times better than blasting. A more academic study [56] on the shot peening effects on fatigue strength showed increased fatigue strength of 7 to 30 % depending on microstructure. Another article also dealing with shot peening of nodular cast iron with different microstructures resulted in 30 to 115 % increase in fatigue strength [59]. Additional work on different nodular cast iron subjected to shot peening showed an increase in fatigue strength between 20 to 50 % once again depending on the microstructure [55]. A 60 % improvement on the fatigue strength was shown on a Cu-Ni austempered nodular cast iron [63].

As a closing comment I would like to state that even though the existent of articles on grey cast iron, or compacted graphite iron, is absent in the context of shot peening and fatigue strength, it can be done and result in increased fatigue strength with the right parameters.

6. Experimental methods

In this chapter of the thesis, the main experiments conducted in this project are presented. All residual stress measurements as well as all of the microstructural studies have been done at the Engineering Materials facilities.

6.1. Shot peening tests

Shot peening is a common method to introduce compressive residual stresses on the surface at a component's critical positions. In general terms the shot peening method is when: "A media is shot on the specimen surface."

Just before impact, the medium has a certain kinetic energy and during impact this energy will to some extent result in plastic deformation of the specimen surface. Plastic deformation is a result of increased dislocation density. As a consequence of this plastic deformation, compressive residual stresses are present at the surface.

Due to the few articles found in the literature concerning shot peening and cast iron, see Chapter 3.4., a few shot peening parameters were chosen as a first starting input. The test subject was a cylindrical pallet that had been mechanically polished on the surface to be peened in order to obtain as similar surface conditions as possible and to minimize the surface hardening effects from machining the test pieces. In Table 1 the parameters chosen to be studied in the beginning of the project are listed.

Table 1: Shot peening parameters chosen in the first experiment

Shot size	Intensity	Resulting Almen Intensity	Coverage
S-170	High/Low	0.37mmA/0.17mmA	100% / 300%
S-330	High/Low	0.30mmA/0.16mmC	100% / 300%
S-550	High/Low	0.17mmC/0.29mmC	100% / 300%

The believed outcome of these tests was to be able to choose appropriate shot peening parameters used to increase the fatigue strength on grey cast iron under axial loading as well as compact graphite iron and grey cast iron under bending fatigue.

6.2. Fatigue testing

The fatigue testing performed within this thesis has been carried out by Ph D Maqsood Ahmad at Volvo Powertrain. The fatigue testing was done in axial loading with $R=-1$ in an electrical high frequency testing machine. Testing frequency was around 125Hz with a failure criteria set to be a 3% change in stiffness. The fatigue life was set to be 10 million cycles meaning that if the test piece survives 10 million cycles then it is regarded to have “infinite” life, also called run-out sample. Both the slope in the low-cycle-fatigue regime and the fatigue strength were to be investigated.

The mechanically polished samples were set to be the reference which a change in fatigue strength should be compared to after shot peening or some other post treatment.

Two different sample geometries were used, having a k_t of 1.05 and 1.33. The argument of the low k_t value instead of a “real” smooth sample having a defined gauge length was for the simplicity of testing. By not having a defined gauge length the crack should start and propagate at the thinnest section of the sample which should lower the scattering in fatigue data. The usage of k_t 1.33 was to test if the material exhibits any notch sensitivity when subjected to post treatments.

The evaluation of the fatigue strength was made by using “staircase”-method also commonly referred to as Dixon and Mood method proposed 1948 [64] which is based on the maximum likelihood estimation. The method provides an approximated formula to calculate both the mean (σ_{fat}) and the standard deviation (σ_{std}) of the fatigue strength assuming that the fatigue strength follows a normal distribution. Also the stress levels needs to be equally spaced in order to use this method.

In practise, first one specifies the stress spacing to be used, and then start the testing at an assumed stress level of the fatigue strength. If the specimen is a run-out then you increase the stress as defined before. On the other hand, if the specimen failed before the defined fatigue life then you lower stress the same amount. By doing so the statistical analyses of the data in terms of the fatigue strength, standard deviation and confidence intervals becomes easier, but still not very easy.

All evaluation of the fatigue data has been done by Ph D Maqsood Ahmad.

6.3. Residual stress profiling

A central part of the project, where this thesis has been carried out, is to measure residual stresses in cast iron. Different surface treatments result in different surface stresses and also different subsurface distributions of the residual stresses. This distribution of stresses in the material affects the fatigue properties, and to get a better knowledge on how the post treatment performed introduces residual stresses can be of high importance. For example can the distribution be of good use when analysing the components fatigue properties. To obtain the residual stress profile with laboratory x-rays, material needs to be removed in small steps since the penetration depth of the x-rays are very shallow. This should be done without introducing any new residual stresses, like those obtained from polishing. To remove material without introducing new residual stresses, electrolytic polishing is the best method to use and it the one conducted in this project. Even though it is practically impossible to remove material without affecting the stress field, with the electrolytic polishing the residual stress distribution will be affected to a minimum. When material is removed the stress field will change and if possible stress corrections due to material removal should be done. In many cases this is practically impossible due to component geometry without FEM-simulations. Another problem, or concern, with electrolytic polish is that every type of edge, due to masking or heterogeneous material, result in a potential peak which led to uneven material removal. A problem to accept and to live with when working with cast iron, to minimize the uncertainty of the amount of material removed several depth measurements have been averaged for every depth.

As described and mentioned earlier in this thesis the $\sin^2\psi$ -method has been used, to measure the residual stresses in the cast iron studied. All measurements have been performed in a four-circle goniometer Seifert X-ray machine. With this method, only the residual stresses in the ferrite are measured. The measured stresses are thus phase stress, the sum of macro and micro stresses in the ferrite. The usage of a Cr-tube for generation of x-rays results in a 2θ angle of approximately 157° for the $\{211\}$ -diffraction plane.

To convert the diffraction data obtained to stresses with the $\sin^2\psi$ -method, a value on the XEC, $\frac{1}{2}S_2$, is needed. In this project that value is $5.81 \cdot 10^{-6}$. Due to the heterogeneity of this material, and that the residual stresses in one of the three phases are measured, lead to calibration of the XEC $\frac{1}{2}S_2$. This calibration has resulted in somewhat un-expected results and need more work to confirm and validate the results. The results and the discussion are excluded in this thesis and the calibration is on-going.

6.4. Microstructural studies

To gain a better understanding on the material behaviour, microstructural investigations in a Hitachi SU-70 FESEM scanning electron microscope have been done. The SEM is equipped with Nordley detector from Oxford Instrument and Channel 5 software, which was used for EBSD mapping of the ferritic phase. From the mapping a low angle grain boundary (LAGB) density can be calculated from the obtained data. The LAGB density plot can then be used to quantify the amount of deformation in the material. Deformation of the microstructure due to polishing and shot peening as well fatigue accumulated deformation after testing have been investigated. New techniques (for these materials) to quantify the deformation behaviour have been tested, i.e. EBSD mapping, to determine the material response and deformation due to loading. With electron channelling contrast image (ECCI), plastic deformation in the material results in clear contrast in the image, as can be seen in the upper left part of Figure 10. These two techniques provide the researcher with a lot of information regarding the deformation in the material.

Figure 10: ECCI of shot peened grey cast iron. The speckled pattern in the upper left is a result from plastic deformation by shot peening. In the middle there is graphite and in the lower right part of the picture, the un-affected material is shown.

SEM investigations have been done on the first test peening that were done on flat cylindrical specimens to get a better understanding on the plastic deformation done by the shot peening conditions tested. The first fatigue testing series were investigated with both ECCI and EBSD. Also fracture surfaces were investigated. The

second fatigue test series with the gentle shot peening condition has also been investigated with ECCI and EBDS as well as some of those that were short time annealed.

7. Appended paper summary

PAPER I

Residual Stresses in Shot Peened Grey and Compact Iron

It is well recognized that shot peening results depend on both the target material and a number of peening parameters. An industrial process is often controlled by choosing peening media, i.e. type of shots and shot size, Almen intensity and degree of peening coverage. Based on the limited publications on shot peening and shot blasting of cast irons found in the literature, twelve unique combinations of shot size, intensity and coverage were chosen. The different shot peening treatments combining different shot sizes, different degrees of coverage and Almen intensities were applied to a grey cast iron and a compact graphite iron having essentially a pearlitic matrix. The induced surface residual stresses and subsurface residual stress distributions as well as plastically deformed depths were investigated by x-ray diffraction.

Relatively high compressive residual stresses have been induced on the surface of all the samples. For both GI and CGI, the largest surface residual stress was found for peening with the smallest shots (S170), low intensity (0.17 mmA) and 100% peening coverage and the lowest surface stress for peening with the largest shots (S550), high intensity (0.29 mmC) and 300% peening coverage. An increased coverage from 100% to 300% had a minor effect on the subsurface residual stress distribution as measurements on selected GI samples show. This is explained by a small effect of further peening on the cyclic deformation behaviour of the cast iron. Peening with a higher intensity, on the other hand, strongly affected the residual stress depth profiles. Also the depth of the compressive zone was greatly increased for both GI and CGI due to a larger depth of plastic deformation. When increasing the shot size, the plastically affected depth does not change pronounced with similar peening intensities, but the residual stress profile and the amount of residual stresses at depth will somewhat differ between the two materials. The better response of CGI to shot peening can be related to its microstructure, especially graphite morphology.

PAPER II

Shot Peening Induced Plastic Deformation in Cast Iron – Influence of Graphite Morphology

To increase the fatigue strength, shot peening of the component is often conducted and proven to be efficient on e.g. steel and aluminium. When shot peening, the shots interact with the surface and result in high level of local plastic deformation. Due to different graphite morphology it is therefore suspected that grey cast iron and compact graphite iron response differently to identical shot peening parameters. While the limited literature available in this field mostly deals with shot peening of nodular graphite cast irons, thus the influence of graphite morphology on shot peening results is not thoroughly investigated. The purpose with this work is to obtain better knowledge on the different plastic behaviours between grey and compact iron. Using electron backscatter diffraction (EBSD) and electron channelling contrast imaging (ECCI) the microstructural changes in the peening affected zone are quantified. The same parameters were used as in Paper I on both materials. With EBSD mapping, LABG density can be calculated, giving information about the plastic deformation distribution from the peening process in depth material.

The better response of CGI to shot peening in the form of larger plastic deformation and higher compressive stresses in the subsurface was attributed to the difference in microstructure, especially graphite morphology, and different capability for plastic deformation of the matrix. Flake graphite inclusions at certain depth can effectively hinder the propagation of plastic deformation into the interior of the sample. Other graphite inclusions do not cause a large reduction of plastic strains of the matrix. All the observed graphite morphologies can locally raise plastic deformation in its surrounding matrix. A higher degree of plastic deformation in the pearlite dominant subsurface regions of compacted cast iron compared to grey cast iron was found. This can be related to the differences in microstructure such as thickness of pearlitic lamellar and density of LABGs.

PAPER III

In-situ SEM/EBSD Study of Deformation and Fracture Behaviour of Flake Cast Iron

Since flake cast iron exhibits brittle failure under tension loading, due to its many graphite tips acting as notches or small cracks that are considered to be initiation points for cracks in the material. The common knowledge on how cracks propagate

in flake cast irons is that the crack initiation point is one or several of the many graphite tips, from the tips the crack propagates along the graphite flakes in the graphite-matrix interface. At strains just before break down, the crack propagates through the matrix and connecting graphite tips. In this study the crack initiation point(s) and crack propagation in a grey cast iron were studied during axial loading in a SEM. Thanks to a specially designed in-situ stage, analysis of the crack initiation and its propagation as well as crystallographic changes was investigated. The microstructural features associated with different strain levels were investigated with SE-mode and EBSD.

From the performed experiment, the fracture behaviour of flake cast iron can be summarized in a few steps of main events. The first noticeable microstructural feature due to the axial loading is the opening of graphite. Graphite flakes opens inside, not all flakes, and this feature can be found in graphite flakes independent of its orientation to the applied load all over the surface. A second important and noticeable event is the delamination of the graphite-matrix interface. Parallel to this event one can see that the graphite that had opened inside opens even more. The third cracking feature is the local plasticity (microplasticity) at graphite tips lying perpendicular to the loading. Fourth and last important feature, before break down, is the bulge of the matrix at the delaminated interface, where the crack later will propagate. Also some of the graphite with an opening inside had also generated a delamination of the graphite-matrix interface. Development of bulges start once the plastic deformation at graphite tips is evidence, but strains resulting in stresses close to and above $\sigma_{ys0.2\%}$ are needed for a bulge to develop. At applied loadings just before rapture the fracture behaviour of flake cast iron results in multiple cracking, which makes it possible for the main crack to “jump” relatively large distances due to the network of flaky graphite. The weakest points in the sample will then link together which results in a rough topography of the fracture surface. As a final occurrence of fracture behaviour in flake cast iron subjected to axial loading the crack propagates in one of the following alternatives:

- Through the opening inside the graphite.
- Through the delaminated interface.
- Via the closest distance between graphite tips where the local plastic deformation results in a ductile-like fracture appearance.
- At the pearlitic grain boundaries leaving a ductile-like fracture.
- Straightforward through the matrix resulting in a cleavage fracture.
- Along the ferrite-cementite interface giving cleavage fracture.

With EBSD changes in grain orientation and LAGBs in flake cast iron due to axial loading was not detected for the set-up used. Analyse of the fractured surface revealed both ductile and cleavage fracture and an increase in fracture topology where multiple cracks was easily detected.

PAPER IV

Fatigue Strength of Machined and Shot Peened Grey Cast Iron

A common opinion is that cast iron, especially grey cast iron, is not as notch sensitive as steel and has therefore not been treated by shot peening to suppress crack initiation. For a heterogeneous material that also is brittle, just like grey cast iron, the shot peening parameters needed to induce beneficial surface residual stresses can be problematic to identify. Fatigue testing under uniaxial loading with an R value of -1, on mechanically polished and shot peened specimens, has been performed to determine the fatigue strength at 10^7 . Two different types of specimen geometries were tested, one smooth and one notched specimen having k_t equal to 1.05 resp. 1.33. With large shots and high peening intensity (S330 shots and 0.16 mm C peening intensity) the fatigue strength clearly decreased whereas small shots and low peening intensity (S70-H shots and 0.07 mmA peening intensity) might have lowered the fatigue strength. A short time annealing at 285°C after gentle shot peening increased the fatigue strength. The results are discussed and explained based on x-ray diffraction measurements, i.e. residual stress and full width at half maximum profiles, as well as microstructural investigations in SEM.

The results showed that in comparison with the mechanically polished specimens, the gentle shot peening specimens had a similar, if not slightly lower, fatigue strength but the heavy shot peening had clearly lower fatigue strength. This could be largely attributed to a negative effect of tensile residual stresses in the subsurface layer, reviled by stress correction due to material removal from the obtained residual stress profiles. Damage in the surface layer in form of microcracking and surface roughness for the heavy shot peened specimens could also contribute to the lower fatigue strength. The positive results on the fatigue strength found after a short time annealing at 285°C on specimens being gently shot peened could be a combination of ageing, associated with Cottrell atmosphere, and recovery of the material. This resulted in increased fatigue strength of 10%, compared to the mechanically polished specimen. However, further works is needed to confirm this.

8. Conclusions

The research presented in this thesis deals with microstructural changes in cast iron after different surface treatments, and its effect on axial fatigue strength. Different surface treatments (in this case) refer to the different shot peening conditions tested so far in the project. To study the changes, a reference condition is needed, and the mechanically polished surface was set to be the reference condition in this project. The changes have been investigated with x-rays (residual stress profiles and FWHM profiles) and in a SEM.

To find shot peening parameters that will increase the fatigue strength of a low ductile material is not easy. Trying to find parameters to a heterogeneous material subjected to shot peening that result in increased fatigue strength is also difficult. Thus finding proper parameters to shot peen cast iron, which has low ductility and is heterogeneous due to the graphite, is not straight forward. The general considered benefits from shot peening have been detected using x-rays in the cast iron specimens subjected to the shot peening parameters used. That is high compressive residual stresses at the surface, reaching a relatively large depth and a clear work hardening of the surface. Despite this, the expected beneficial effects from shot peening have not been observed in axial fatigue loading.

From the specimens studied it becomes clear that the fracture process is very complicated, with multiple cracking and crack networking and crack linking, which slows down the analyses. Making it more problematic to state clear conclusions since so many things contribute, different deformation mechanisms in and between the phases depending on the loading, to the observed phenomenon.

Grey cast iron specimens shot peened very gently and annealed at 285°C for 30 minutes showed an increase in fatigue strength in axial loading with $R=-1$. Only the gentle shot peening might have resulted in a low increase in fatigue strength but after annealing the fatigue strength was clearly increased perhaps due to interstitial diffusion in a Cottrell atmosphere locking dislocations and some recovery of the surface.

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