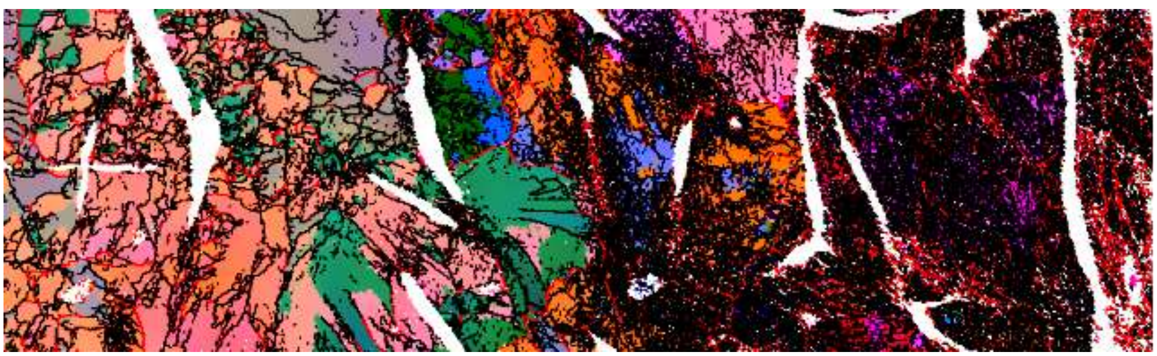
Technical Final Report – Confidential

Increased fatigue strength of cast iron components through optimization of residual stresses



Project within FFI Vehicle Development program

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Content

1. Executive summary

Cast irons are state of the art materials for cylinder heads in heavy-duty diesel engines. Demands on fuel economy, low emissions and increasing engine power are constantly increasing. To meet the high demands set on fatigue strength, current materials must either be replaced or improved. Replacing the currently used grey iron with, *e.g.*, compacted graphite cast iron (CGI) is neither trivial nor straightforward.

Residual stresses are internal stresses that are independent on applied loading. These stresses have a significant effect on the fatigue behavior of materials: tensile residual stresses are usually considered as detrimental while compressive stresses are considered as beneficial in terms of fatigue strength. Improving the grey cast iron by optimizing the residual stress for example through shot peening on critical locations state offers a lucrative and cost effective solution. To be able to optimize the residual stress state, the build-up of these stresses during different manufacturing processes needs to be fully understood.

The main goal of this project is to increase the fatigue strength of cast iron components by 20% through optimization of residual stresses. The increased fatigue strength also facilitates a decrease in weight through thinner wall sections. Methods for fast and reliable measurement of residual stresses are also developed. Increased understanding of the correlation between residual stresses and fatigue life as well as understanding and competence in the area of residual stresses in inhomogeneous, especially cast materials is also desired.

The project has been carried out in collaboration with the Division of Engineering Materials of Linköping University, Volvo Trucks Technology and Scania CV AB in the time frame of January 1st 2011 to December 31st 2013. Linköping University has been responsible for most of the theoretical work, residual stress measurements and studies using scanning electron microscopy (SEM, EBSD). Scania and Volvo have been responsible for manufacturing the specimens, finding suppliers for the surface treatments and carrying out the fatigue tests.

The results of the project showed that gentle shot peening increases the *bending* fatigue strength of compacted graphite iron (CGI) by at least 20% and that of grey cast iron (LGI) by at least 10%. Gentle shot peening combined with a short time annealing increases the *axial* fatigue strength of grey iron by about 10% but a heavy shot peening reduces the *axial* fatigue strength of both smooth and notched specimens by about 20%. CGI responds somewhat better to shot peening than grey iron in the form of larger plastic deformation and compressive residual stresses in the subsurface. All the shot peening treatments studied in the current project (conventional, ultrasonic at Sonats in France, trials at Clausthal University) can induce relatively high surface compressive residual stresses. Also a cooling channel of a Scania cylinder head was shot peened and tested in a component testing rig. Due to limited testing capacity, the amount of tests carried out was unfortunately small. Based on the total of six cylinder heads that were tested no definitive conclusions on either positive or negative effect of shot peening on the fatigue strength can be drawn.

The studies carried out in the project showed that X-ray diffraction is the best available method to determine the near surface residual stress state. Neutron diffraction (ND) RS-measurements made at Paul Scherrer Institute (PSI) in Switzerland on stress harps from Volvo showed a qualitative agreement with FE-simulations.

The project has successfully shown that it is possible to significantly increase the fatigue strength of cast irons through optimization of residual stresses. The main goal of the project, 20% increase in fatigue strength, was reached for specimens in compacted graphite iron in cast condition and for grey cast iron in machined condition. The project has created a lot of new knowledge on the correlations between fatigue strength, graphite morphology, residual stresses and surface quality in cast irons. Also the fact that a fatigue strength can be significantly *decreased* through heavy shot peening in axial loading is extremely interesting and will give valuable input to studies on clean blasting effects.

The results of the project have been presented both in scientific papers and conference proceedings as well as internal seminars both at Scania and Volvo. The licentiate thesis "*Residual Stresses and Fatigue of Shot Peened Cast Iron*" consisting of the research work carried out within the project was presented at LiU in November 2013.

A two year continuation project will likely be granted for further studies in the area, especially the short time heat treatment after shot peening and studies on the current clean blasting process offer promising ways to improve the fatigue strength of cast irons for a low cost.

2. Background

Residual stresses are internal stresses that are independent on applied loading. In fatigue loading, these stresses can be considered as inherent mean stresses that have a significant effect on the fatigue behavior of materials. Tensile residual stresses are usually considered as detrimental with respect to fatigue strength because a high tensile mean stress (*i.e.*, tensile residual stress) reduces the applicable tensile loading amplitude. Compressive residual stresses, however, are considered as beneficial in terms of fatigue strength.

Shot peening is a cold working process in which the surface of a part is bombarded with a small spherical media called shot. The method is widely used to increase the fatigue strength of steel components such as springs and gears. The beneficial effect of shot peening is mainly due to the induced compressive stress state and increased surface hardness that are achieved through cold working of the surface. A process similar to shot peening, clean blasting, is widely used to clean the cast components from sand etc. The process is, however, not as controlled as shot peening.

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 strength.

As the combustion pressure of heavy truck engines increases due to higher demands on engine power, fuel economy and emissions, the applied cyclic load on the cylinder heads increases. One way to meet the increasing requirements could be to optimize the residual stress state of the cylinder heads.

Since shot peening is widely used to increase the fatigue strength of steels, it might also be used to increase the fatigue strength of cast iron. However, shot peening or the effect of residual stresses on the fatigue strength of cast irons, especially grey cast iron, has not been studied extensively.

A number of experimental techniques, including diffraction, hole-drilling, magnetic, ultrasonic and mechanical sectioning methods, have been developed for analyzing residual stresses in engineering materials. Among them, x-ray diffraction (XRD) and hole-drilling are two well established and most popular techniques used by the industry. The XRD measurement of residual stresses on cast iron is not straightforward mainly due to the rather inhomogeneous microstructure with large grains and graphite inclusions and varying elastic properties.

In addition to x-rays, the more recently established neutron and synchrotron (high energy x-rays) diffraction techniques can be considered as a comparative/verification method to x-ray diffraction. Their advantages over the conventional x-rays are attributed to their large penetration depth in metals, which allows non-destructive measurements of depth profiles of residual stresses. It could therefore be used for analyzing, *e.g.*, thermally induced residual stresses in cast irons. Like x-ray diffraction, when applied on materials with an inhomogeneous microstructure, precautions are needed to minimize uncertainties in the measured stress value. There are a number of synchrotron and neutron facilities for residual stress analysis in Europe and many of them are open to EU users. In this project neutron diffraction measurements are carried out at Paul Scherrer institute in Switzerland.

The aim of this research project is to increase the fatigue resistance of cast iron components used in heavy vehicles by optimization the residual stress state. The main emphasis is on the material that is currently used in cylinder heads, *i.e.*, grey cast iron but also compact graphite iron is studied. Means to induce beneficial residual stresses are investigated, and the correlation between residual stress state and fatigue resistance under relevant loading conditions are established.

3. Objective

The main objective of the project has been to increase the fatigue strength of cast iron components by 20% through optimization of residual stresses. This is needed in order to meet the ever increasing demands set on the cast iron components in heavy trucks. Optimization of residual stresses includes development of different types of surface treatments that induce beneficial residual stresses. These surface treatment methods could also decrease the deviation in fatigue behavior.

The measurement of residual stresses on inhomogeneous materials such as cast iron is not straightforward, and therefore more reliable methods should be developed. Increased understanding of the correlation between residual stresses and fatigue life in cast components as well as understanding and competence in the area of residual stresses in inhomogeneous, especially cast materials is also desired.

4. Project realization

The project has been carried out in collaboration with the Division of Engineering Materials at Linköping University (LiU), Volvo Powertrain and Scania CV AB in the time frame of January 1st 2011 to December 31st 2013. Ph D student Mattias Lundberg has been responsible for most of the operative work at LiU and has been supervised by Ass. Prof. Ru Lin Peng. A working group consisting of the abovementioned persons and representatives from Volvo (Dr Maqsood Ahmad) and Scania (Dr Taina Vuoristo and Dr Daniel Bäckström).

Linköping university has been responsible for most of the theoretical and practical work concerning the build up and measurement of residual stresses in cast iron specimens and components. The residual stresses on the specimens from shot peening tests were measured using the X-ray diffractometers at LiU. These included also measurements on specimens that were tested for fatigue. LiU initiated collaboration with Paul Scherrer Institute in Switzerland and performed measurements on both stress harps and cylinder heads using neutron diffraction technique. The fatigue test specimens have been studied at LiU using scanning electron microscopy (SEM) with electron backscattering diffraction (EBSD) to analyze the effect of shot peening on surface deformation of the two types of cast irons. LiU has been responsible for writing the articles and conference presentations published within this project with help from the other partners.

Volvo and Scania contributed by delivering specimens and components for shot peening and fatigue tests. They also assisted in developing the parameters for shot peening and found the suppliers for the different surface treatments. Volvo initiated collaboration with Clausthal University that made a number of shot peening tests. Scania made some ultrasound shot peening tests at Sonats in France but most of the shot peening tests were made at Ytstruktur AB in Arboga.

The fatigue tests for the surface treated specimens were carried out by Volvo and Scania. The fatigue test results were also analyzed by respective company. Component testing for cylinder heads that were shot peened inside a cooling channel was performed at Scania. Volvo performed casting simulations on stress harps for comparisons with experimental residual stress data from neutron diffraction measurements, and Scania delivered material and performed casting simulations for similar tests on cylinder heads.

The results of the work performed by LiU, Volvo and Scania were discussed in telephone and other meetings with the working group. A steering group consisting of representatives from all three parts supervised and commented the progress of the work.

5. Results and deliverables

Before the project was started, very few literature references on the beneficial effect of shot peening on the fatigue strength of cast iron, especially grey cast iron, were found. Therefore, there was a risk that shot peening or other similar surface treatments would not give a positive effect on the fatigue properties. The project has, however, successfully shown that it is possible to significantly increase the fatigue strength of cast irons through optimization of residual stresses.

The main goal of the project, 20% increase in fatigue strength, was reached for specimens in compacted graphite iron in cast condition and for grey cast iron in machined condition. However, due to limited amount of test data, we failed to prove that the same increase in fatigue strength can be achieved for cylinder heads that were shot peened inside a cooling channel.

During the course of the project the project partners have gained extremely valuable knowledge on the effects of residual stresses, surface quality and graphite morphology on the fatigue behavior of cast irons. For example, it was found that heavy shot peening combined with axial loading could significantly *decrease* the fatigue strength of cast irons.

The project has resulted in nine scientific publications (see 6.2) where the results of the project are reported and discussed.

In the following some of the main results of the project are briefly presented.

Increase in fatigue strength

The results of the fatigue tests carried out in axial loading at Volvo and in bending at Scania are summarized in Figure 1. The resulting increase depends greatly on the shot peening method (heavy vs. gentle), reference condition (machined vs. as cast) and type of loading (axial vs. bending).

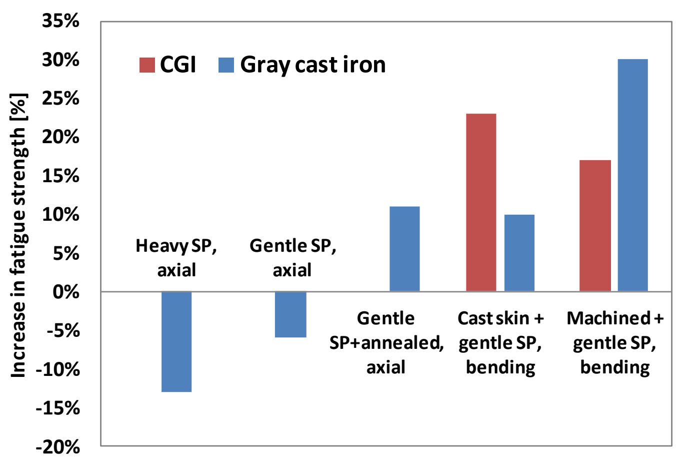
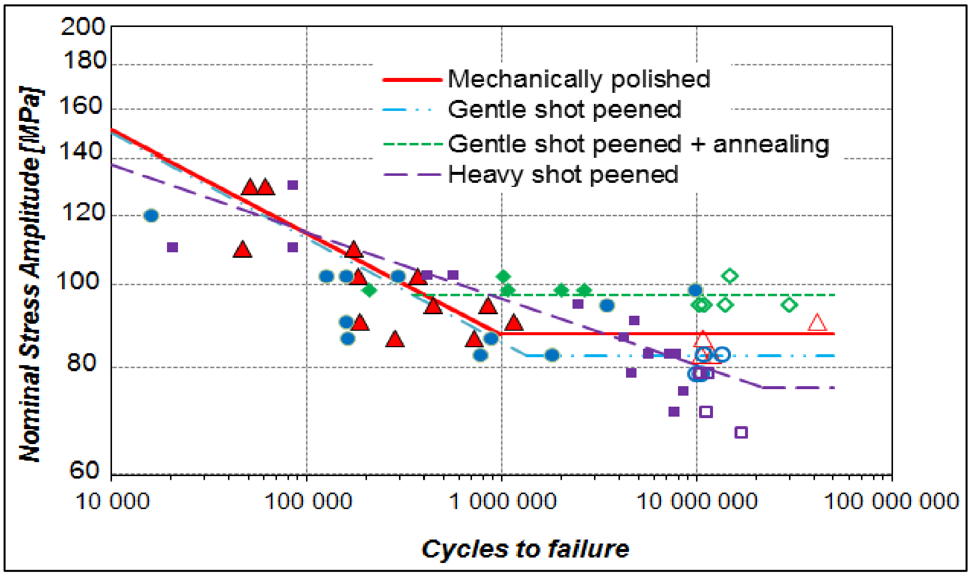


Figure 1. Summary of the effect of shot peening on the fatigue strength of grey cast iron and CGI (compacted graphite iron) specimens in axial and bending loading.

Figure 2 shows the results of axial fatigue tests carried out at Volvo. The table below the Wöhler curves summarizes the results of the tests for different shot peening processes and the combined short heat treatment.

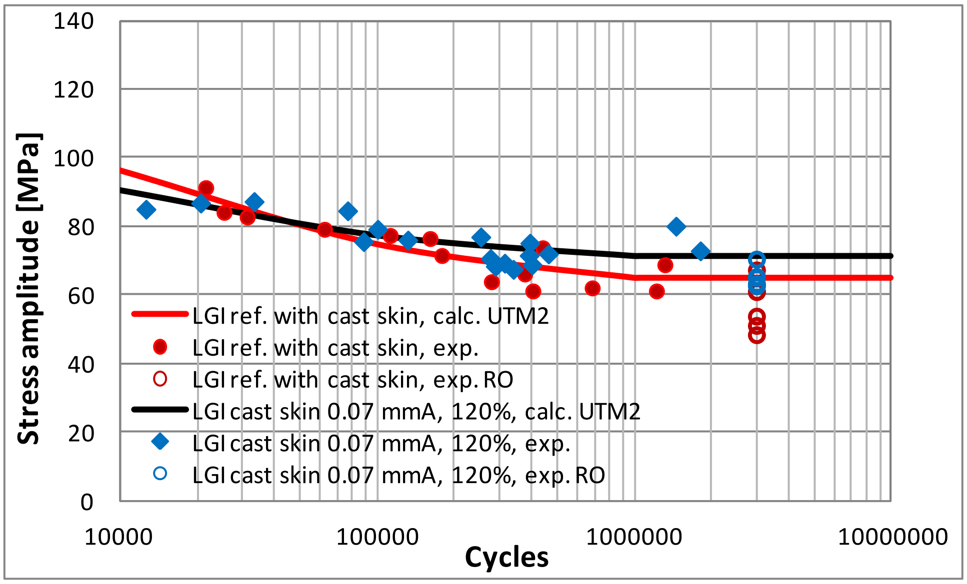


	Mechanically polished	Heavy SP (0.55 mmA, 100%)	Gentle SP (0.07 mmA, 120%)	Gentle SP + annealed
Fatigue limit [MPa]	87.4	75.8	82.5	97.3
Standard deviation [MPa]	4.6	8.8	2	2
Standard deviation [%]	5%	12%	2%	2%
Effect of shot peening / heat treatment [%]	-	-13%	-6%	11%

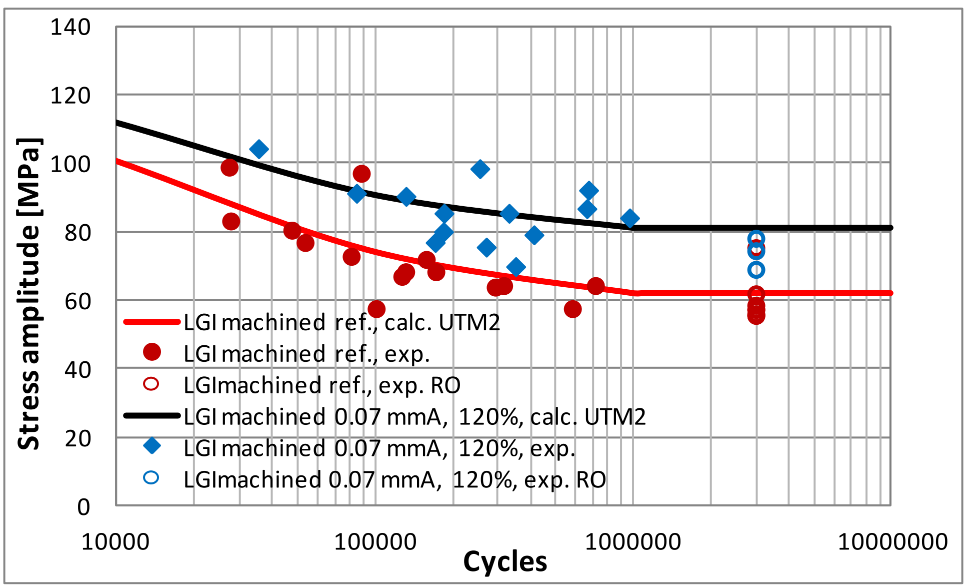
Figure 2. Results of the axial fatigue tests on grey cast iron carried out by Volvo for notched specimens (K_t=1.33) and R=-1.

The results from the bending fatigue tests carried out by Scania for grey cast iron in as cast and machined conditions before and after shot peening are shown in Figure 3. Results for compacted graphite iron (CGI) with the same reference conditions but with several shot peening parameter combinations are presented in Figure 4. The shot peening processes tested at Scania can all be considered as “gentle”, since the intensity is 0.10 mm Almen A or less. The exponent given in the tables is the slope of the Wöhler curve at 10^5 cycles.

Gentle shot peening increases the *bending* fatigue strength by at least 20% and 10% for CGI and grey cast iron, respectively. Gentle shot peening combined with a short time annealing at a relatively low temperature (285°C) increases the *axial* fatigue strength of notched specimens of grey iron by about 10%. Heavy shot peening *reduces the axial* fatigue strength of both smooth and notched specimens by about 20% [Publ. 1, 4]. As shown in Figure 1, CGI responds somewhat better to shot peening than grey iron in the form of larger plastic deformation and compressive RS in the subsurface, which lead to higher fatigue strength.



3a)



3b)

Grey cast iron	Non-shot peened, cast skin	Cast skin, 0.07 mmA, 120%	Non-shot peened, machined	Machined, 0.07 mmA, 120%
Fatigue limit [MPa]	65	71	62	81
Standard deviation [MPa]	4	4	9	8
Standard deviation [%]	6%	6%	14%	10%
Exponent at 10^5 cycles	10	17	8	12
Effect of shot peening [%]	-	10%	-	30%

Figure 3. Results of the bending fatigue tests (R=0.1) for grey cast iron (LGI) carried out at Scania: 3a) specimens with cast skin before and after shot peening, and 3b) machined and thereafter shot peened specimens.

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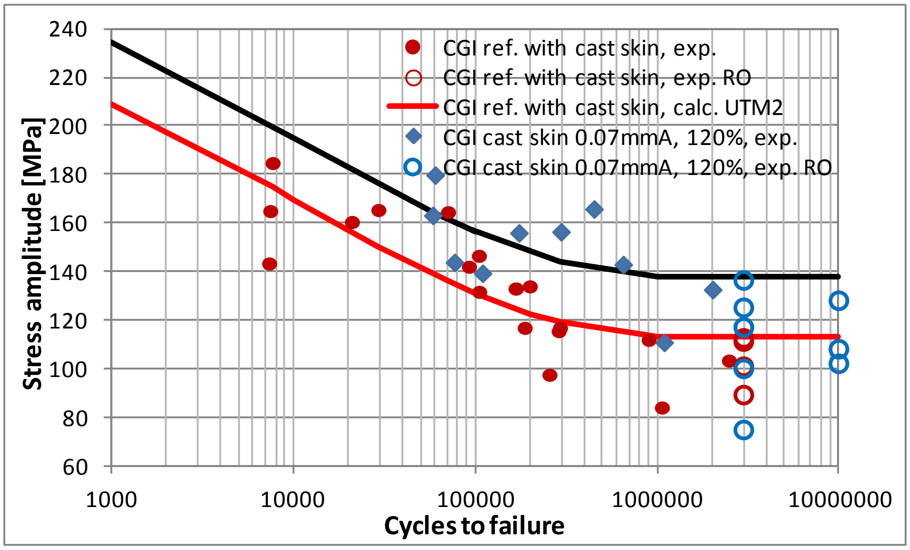
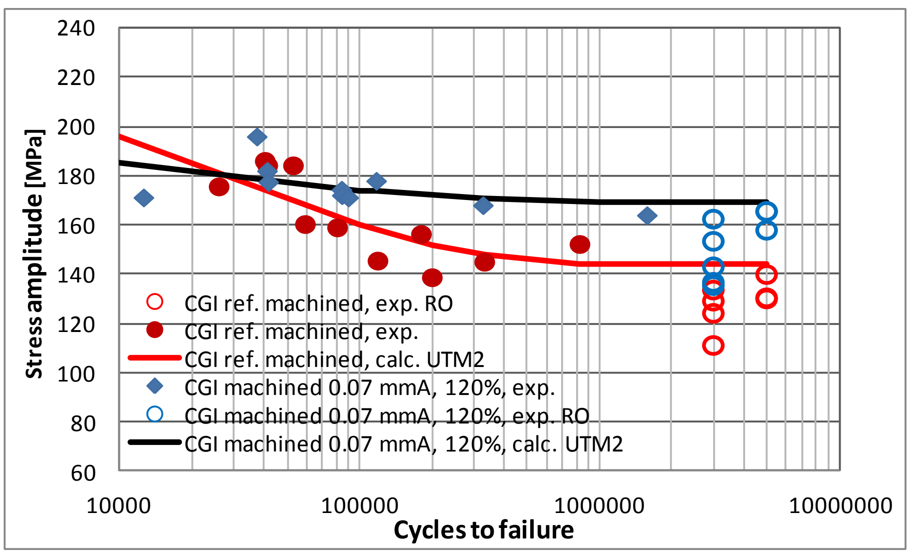


4a)

CGI, cast skin	Non-shot peened	0.07 mmA, 80%	0.07 mmA, 120%	0.1 mmA, 80%	0.1 mmA, 120%
Fatigue limit [MPa]	113	122	138	139	133
Standard deviation [MPa]	16	12	17	7	8
Standard deviation [%]	14%	10%	12%	5%	6%
Exponent at 10^5 cycles	10	7	11	11	10
Effect of shot peening [%]	-	8%	22%	23%	17%



4b)

CGI, machined	Non-shot peened	0.07 mmA, 80%	0.07 mmA, 120%	0.1 mmA, 80%	0.1 mmA, 120%
Fatigue limit [MPa]	144	161	169	165	157
Standard deviation [MPa]	11	6	8	10	7
Standard deviation [%]	8%	4%	5%	6%	4%
Exponent at 10^5 cycles	13	29	46	35	16
Effect of shot peening [%]	-	12%	17%	15%	9%

Figure 4. Results of the bending fatigue tests (R=0.1) for CGI (CGI400) carried out at Scania: 4a) specimens with cast skin before and after shot peening with different parameters (see Table 4a), and 4b) machined and thereafter shot peened specimens.

Component testing

Towards the end of the project a cooling channel inside a Scania cylinder head was successfully shot peened using the same parameters that gave the best result in bending fatigue tests (see Table 1).

Table 1. Shot peening of Scania's cylinder heads at Ytsruktur Arboga.

Shot peening parameters

- Manual shot peening with a lance
- Media steel S70 H (55-62HRC) according to AMS 2431/8
- Coverage 120%, intensity 0.07 mmA
- Coverage check using Peenscan and 10x magnification
- Cleaning using pressurized air

The shot peened cylinder heads were tested at Scania in a rig where a pulsating load is applied on the combustion plane. Unfortunately, the possibilities to test these cylinder heads were limited, and only six heads were tested. After the tests the cylinder heads were cut in sections to detect possible fatigue cracks.

The effect of shot peening in the cooling channel could not be verified through these tests. The tested cylinder heads showed lower fatigue strength as expected based on the results from bending fatigue tests on test specimens. Unfortunately there were no reference cylinder heads available for testing from the same casting batch, and thus the fatigue strength of the shot peened cylinder heads before shot peening could not be verified. The results from this study indicate, however, a lower fatigue strength than previous testing of cylinder heads with the same part number.

Fast and reliable methods to measure residual stresses

The experiences from the project showed that X-ray diffraction is the best available method to determine the near surface residual stress state. In-situ X-ray diffraction experiments revealed that the X-ray elastic constants needed for an accurate residual stress analysis are both material and load dependent [Publ. 6].

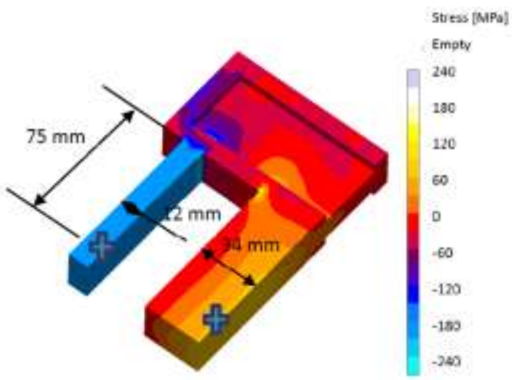
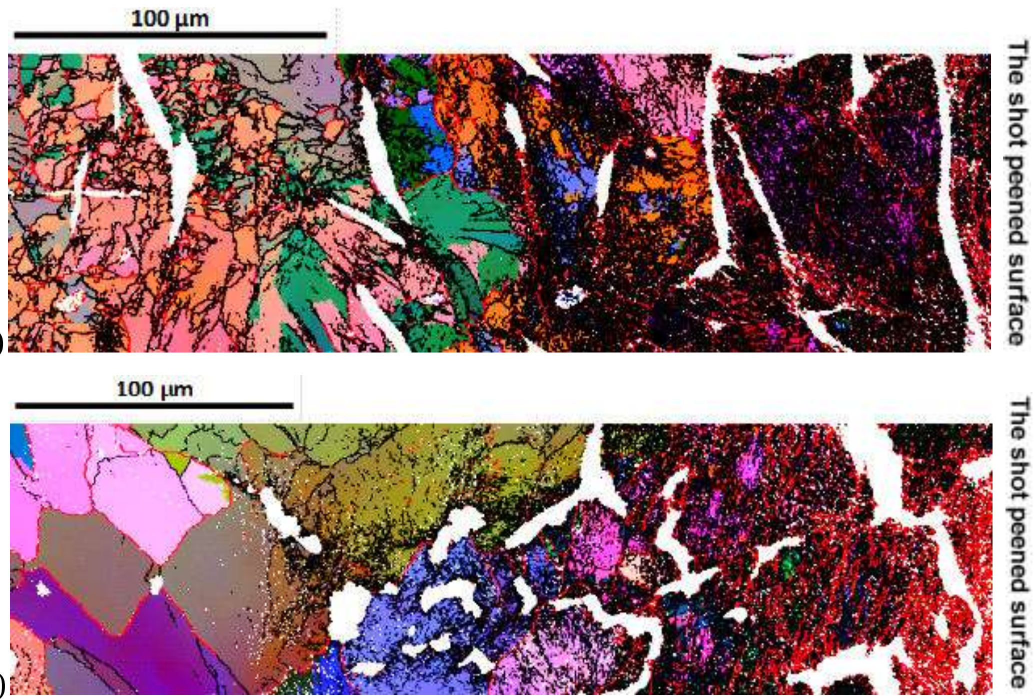


Figure 5. Simulated axial residual stress distribution in the as cast stress harp.

Residual stresses were analyzed in an as cast and an annealed stress harp by finite element modeling (Fig. 5) and the results were compared with neutron diffraction and hole drilling measurements. The neutron diffraction measurements were carried out at Paul Scherrer Institute (PSI) in Switzerland. For the as cast harp, good agreement was found between the simulation and neutron diffraction measurements in the normal and transverse directions with low residual stresses. Discrepancy occurs in the axial direction and especially in the side bars for which the simulation shows much higher compressive residual stresses. All the three methods give low residual stresses in the annealed harp [Publ. 9]. For the ND measured cylinder heads from Scania, the agreement with casting simulations was rather poor.

Methods to predict and induce beneficial residual stresses

All shot peening treatments studied in the current project (conventional, ultrasonic at Sonats in France, trials at Clausthal University) can induce relatively high surface compressive residual stresses in cast irons. Large test series with conventional shot peening showed that the largest surface residual stressed were induced for peening with the smallest media, low intensity and 100% peening coverage. The lowest surface stresses were obtained with the heaviest parameters. Shot peening with a higher intensity strongly increased the depth and magnitude of compressive residual stresses [Publ. 1, 2].



a) b)

Figure 6. Increased density of low (LAGB) and high (HAGB) angle boundaries near the surface of LGI and CGI by shot peening are shown as black (LAGB) and red (HAGB) lines.

Two types of materials, grey cast iron (LGI) and compacted graphite iron (CGI), were studied in this project. Both fatigue tests, residual stress measurements and microstructural analyses showed that CGI responds better to shot peening than LGI in the form of larger plastic deformation, higher compressive stresses and larger increase in fatigue strength. The better response of CGI is explained by differences in the graphite morphology and the matrix capability to plastic deformation. The effects of microstructure and morphology were studied using electron backscattering diffractometry (EBSD) and an example visualizing the plastic deformation in form of increased density of low and high grain boundaries due to shot peening in the surface layers of the two materials is shown in Fig. 6 [Publ. 1, 3].

Better understanding of the correlation between residual stresses and fatigue life in cast components

The studies carried out by LiU on the shot peened and fatigue test specimens have lead to deeper understanding on the dependencies between residual stresses, surface quality (e.g., as cast vs. machined) and fatigue strength. [Publ. 1, 4, 5]

5.1 Delivery to FFI-goals

The project has in many ways contributed to the goals of both the FFI program "*Vehicle Development*" and the subprogram "*Material for more efficient vehicles*".

The project has led to a close and fruitful collaboration between the Division of Engineering Materials at LiU, Scania and Volvo Trucks Technology. In addition, the project has included close collaboration with a supplier to automotive industry in Sweden, Ytstruktur Arboga AB, who has together with the project partners developed methods for shot peening of cast irons and cast iron components. These collaborations strengthen the research and innovation capacity in Sweden and contribute to the objective to secure competitiveness and employment.

International research collaboration has also been frequent in terms of neutron diffraction measurements at PSI in Switzerland, shot peening tests and consultation in collaboration with Clausthal University and ultrasonic shot peening tests at Sonats in France.

The results of the project contribute to the goals of the subprogram by offering methods to significantly increase the fatigue strength of cast irons. Especially grey cast iron is a rather inexpensive material, and with methods like shot peening costly changes of material can be avoided and the loading range of the components manufactured of cast iron increased by introducing shot peening instead. Thus, the two goals, substantial cost reduction and significantly better material properties, can be fulfilled using the methods studied in this project.

6. Dissemination and publications

6.1 Knowledge and results dissemination

The results in the project are mostly obtained for specimens that are shot peened and tested for fatigue. The results of the project have not yet been directly implemented in either Scania's or Volvo's products.

Most of the project results have been reported in public, scientific journals and conference presentations. Licentiate thesis “*Residual Stresses and Fatigue of Shot Peened Cast Iron*” was presented by Mattias Lundberg at LiU in November 2013. In order to spread the knowledge gained during the project within the participating industries, internal seminars and presentations on the project results have been given both at Scania and Volvo.

6.2 Publications

The results of the project have been published in scientific journals and conference proceedings. A complete list of publications is given below.

1. Mattias Lundberg: Residual Stresses and Fatigue of Shot Peened Cast Iron, Licentiate Thesis, Linköping University, 2013.
2. M Lundberg, R L Peng, M Ahmad, T Vuoristo, D Bäckström, and S Johansson: Residual Stresses in Shot peened Grey and Compact Iron, accepted for publication in HTM Journal of Heat Treatment and Materials.
3. M Lundberg, R L Peng, M Ahmad, D Bäckström, T Vuoristo and S Johansson: Shot Peening Induced Plastic Deformation in Cast Iron, accepted for publication in HTM Journal of Heat Treatment and Materials.
4. M Lundberg, R L Peng, M Ahmad, D Bäckström, T Vuoristo and S Johansson: Fatigue strength of machined and shot peened grey cast iron. Accepted for publication in Advanced Materials Research, to be presented in Fatigue 2014 Melbourne, Australia, 2-7 March 2014.
5. M Lundberg, R L Peng, M Ahmad, T Vuoristo, D Bäckström, S Johansson: Fatigue strength on shot peened compacted graphite iron, abstract submitted to ICSP12 (International conference on Shot Peening, 2014)
6. M Lundberg, R L Peng, T Vuoristo, D Bäckström,M Ahmad, S Johansson: Influence of Microstructure on the XECs of Cast Irons, abstract submitted to ECRS-9.
7. M Lundberg, R L Peng, M Ahmad, D Bäckström, T Vuoristo and S Johansson: Influence of Shot Peening Parameters on Residual Stresses in Flake and Vermicular Cast Irons, Materials Science Forum, Vols. 768-769, pp.534-541.
8. M Lundberg, R L Peng, M Ahmad, D Bäckström, T Vuoristo and S Johansson: Graphite Morphology´s Influence on Shot Peening Results in Cast Irons, The 9th International Conference on Residual Stresses, 2012, Materials Science Forum, Vols. 768-769, pp.542-549.
9. P Schmidt, R L Peng, V Davydov, M Lundberg, M Ahmad, T Vuoristo, D Backström, S Johansson: Analysis of Residual Stress in Stress Harps of Grey Iron by Experiment and Simulation, to be presented in ECRS-9, 2014.

7. Conclusions and future research

The project has resulted in a close collaboration between LiU, Scania and Volvo. The results of the project have been published in a licentiate thesis, a number of international scientific publications and internal seminars.

Before the project was started, very few literature references on the beneficial effect of shot peening on the fatigue strength of cast iron, especially grey cast iron, were found. Therefore, there was a risk that shot peening or other similar surface treatments would not give a positive effect on the fatigue properties. The project has, however, successfully shown that it is possible to significantly increase the fatigue strength of cast irons through optimization of residual stresses. The main results can be summarized as:

- Gentle shot peening increases the bending fatigue strength by at least 20% and 10% for CGI and grey cast iron, respectively.
- Gentle shot peening combined with a short time annealing increases the axial fatigue strength of notched specimens of grey iron by about 10%.
- Heavy shot peening reduces the axial fatigue strength of both smooth and notched specimens by about 20%.
- Long time annealing of gently shot peened specimens shows similar fatigue life as the reference specimens due to thermal relaxation of residual stresses (RS).
- CGI responds somewhat better to shot peening than grey iron in the form of larger plastic deformation and compressive RS in the subsurface.
- X-ray diffraction is the best available method to determine the near surface RS state. In-situ X-ray diffraction experiments revealed that the X-ray elastic constants needed for an accurate RS analysis are both material and load dependent.
- Neutron diffraction (ND) RS-measurements made at Paul Scherrer Institute (PSI) in Switzerland on stress harps from Volvo showed a qualitative agreement with FE-simulations. For the ND measured cylinder heads from Scania, the agreement with casting simulations was rather poor.

Due to the promising results gained in this project, a two year continuation project will likely be granted for further studies. Especially the short time heat treatment after shot peening and studies on the current clean blasting process offer promising ways to improve the fatigue strength of cast irons at a low cost. The results of the continuation project will be summarized in a doctoral thesis.

8. Participating parties and contact persons

The project has in collaboration between Division of Materials Engineering at Linköping University, Scania CV AB and Volvo Trucks Technology. The contact persons are:

Linköping University, Division of Engineering Materials:
Associate professor Ru Lin Peng, ru.peng@liu.se
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