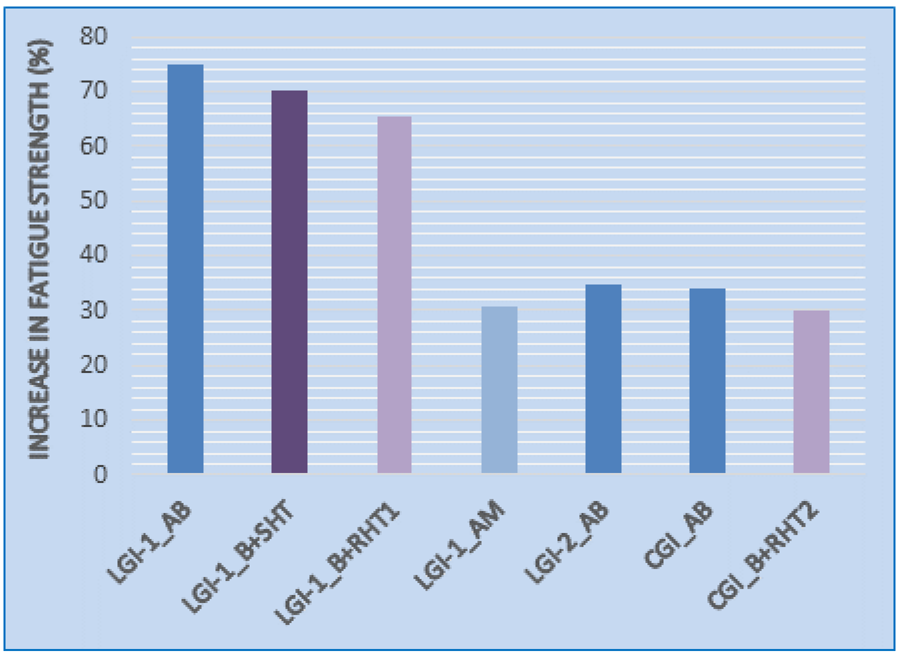
Increased fatigue strength of cast iron components through optimization of residual stresses-Part II



Project within FFI Vehicle Development program

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Content

FFI in short

FFI is a partnership between the Swedish government and automotive industry for joint funding of research, innovation and development concentrating on Climate & Environment and Safety. FFI has R&D activities worth approx. €100 million per year, of which half is governmental funding. The background to the investment is that development within road transportation and Swedish automotive industry has big impact for growth. FFI will contribute to the following main goals: Reducing the environmental impact of transport, reducing the number killed and injured in traffic and Strengthening international competitiveness. Currently there are five collaboration programs: **Vehicle Development, Transport Efficiency, Vehicle and Traffic Safety, Energy & Environment and Sustainable Production Technology.**

For more information: www.vinnova.se/ffi

1. Executive summary

Cylinder heads for heavy truck applications are mainly produced of grey cast iron (LGI) which has a number of advantages. As the combustion pressure of heavy truck engines increases to meet the increased demands on engine power, fuel economy and emissions, the 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, through which the fatigue strength can be enhanced. A cylinder head is only one example of a component whose loading is directly affected by the increasing demands.

Shot peening is commonly used to increase the fatigue strength of steels. The beneficial effect of shot peening is mainly due to the compressive residual stresses induced close to the surface. Also the increased hardness and in some cases better surface roughness contribute to the improved fatigue strength. The effect of shot peening on the fatigue strength of cast irons, especially grey cast iron, has not been studied extensively. Blast cleaning, an industrial process for effective removal of casting residues, can be viewed as an uncontrolled high intensity shot peening process. Depending on blasting parameters used, the resulting residual stresses and surface roughness vary significantly. Literature on the effect of blast cleaning on fatigue strength of grey cast iron is also scarce.

The current project (Part II) is the continuation of a VINNOVA/FFI-project (nr 2009-4145, January 2011-December 2013, Part I). The primary goal of both parts is to increase the fatigue strength of LGI and even compacted graphite iron (CGI) through optimization of residual stresses. Cylinder heads of heavy duty truck engines are the target components for the use of findings from the project. The results from Part I raised several interesting issues and indicated possibility for further improvement in fatigue strength. Among them, short time annealing appeared to increase the axial fatigue strength of notched LGI, however, long time annealing at a lower temperature removed the benefit of gentle shot peening on bending fatigue of CGI. Furthermore, heavy shot peening reduced the axial fatigue strength and the severe damage it induced in the surface resembled that in blast cleaned components. Blast cleaning can be viewed as an uncontrolled heavy shot peening process. The following main objectives have therefore been defined for Part II.

- Increase the fatigue strength of grey cast iron by 15% and that of CGI by 30% through surface treatments and short time annealing
- Identify a critical service temperature for shot peened cast components
- Quantify the effect of current clean blasting process on fatigue strength and suggest improved process
- Complete one PhD thesis with additional 3-5 scientific publications

Part II (nr 2013-05598) was planned for the period April 2014 to March 2016. However, the PhD student who worked in Part I went on sick leave shortly before Part II started. The project work started as planned but the work that Linköping University (LiU) was responsible for have been carried out partly by senior researchers. Agreed by all partners and approved by Vinnova, the project period has been extended by a half year, to be completed by September 2016.

The results from Part II showed that blast cleaning processes and thus shot peening processes with proper intensity can greatly increase the fatigue strength of LGI and CGI castings. The processes currently used by Volvo and Scania all give a significant increase, about 75% in bending fatigue limit for Volvo blasted LGI and about 34% for Scania blasted CGI and LGI, mainly due to compressive residual stresses in a larger depth and hardening of the soft casting skin. The results revealed the potential of optimization of Scania's process for better fatigue performance. With the positive effect of blasting, some work, especially the planned heat treatments on shot peened specimens, were carried out on blast cleaned specimens instead. The findings from blast cleaning given below are in principle also valid for shot peening. It was observed that the optimal heat treatment (20 to 30 minutes at 285 ^{o}C) for strengthening did not enhance the fatigue limit of Volvo blasted LGI but reduced the gain in bending fatigue limit from 75% to 71%. The service temperature effect differs between the LGI and CGI and also seems to depend on the intensity of blasting. A long term exposure of Volvo blasted LGI to 120 ^{o}C, estimated service temperature for the cooling channels of cylinder heads, reduced the improvement in fatigue limit from 75% to 67%, while a long time annealing of Scania blasted CGI at 220 ^{o}C, estimated highest service tempearture for cylinder heads, decreased the benefit of blasting from 34% to 28%. Finally, the research work resulted in the publication of three conference papers and three more conference/journal papers are under preparation. It can be concluded that the main goal of the project, to increase the fatigue strength of grey cast iron and compacted graphite iron, through optimization of residual stresses, is met. On the other hand, as the PhD student was not engaged in Part II, no PhD thesis was delivered.

The research work has contributed to better understanding of the influence of surface mechanical treatment on fatigue behaviour of cast irons and the correlation between treatment parameters and surface microstructure and conditions.

2. Background

Cylinder heads for heavy truck applications are mainly produced of grey cast iron. Grey cast iron (LGI) exhibits a number of positive physical properties such as high thermal conductivity and high damping capacity. The geometric complexity of the cylinder head also limits the selection of materials and manufacturing methods. The downside of using LGI is its relatively low strength. 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 with gas pressure but also a varying thermal load is applied. In addition to high resistance for high cycle fatigue at elevated temperatures, the scatter in fatigue strength should also be minimized. One way to meet the increasing requirements could be to optimize the residual stress state of the cylinder heads. A cylinder head is only one example of a component whose loading is directly affected by the increasing demands.

Shot peening is commonly used to increase the fatigue strength of steels. The beneficial effect of shot peening is mainly due to the compressive residual stresses induced close to the surface. The effect of shot peening on the fatigue strength of cast irons, especially grey cast iron, has not been studied extensively.

A Vinnova/FFI project on this topic was initiated in 2009 and started in 2010 by Scania, Volvo and LiU (nr 2009-nr4145). About 20% and 10% increase in bending fatigue limit was obtained for compacted graphite cast iron (CGI) and LGI, respectively. The selection of proper shot peening parameters was proved to be essential: heavy shot peening resulted in 20% decrease in the axial fatigue strength of LGI. Promising test results, 10% increase in axial fatigue limit, were obtained after a short time annealing of gently shot peened notched LGI samples at a relatively low temperature. A positive effect of short time annealing on fatigue strength, tensile strength or hardness has previously been reported by other researchers for steels and cast iron[1]. The mechanism behind the phenomenon is not fully known but static strain ageing effects could offer a possible explanation. In order to further utilize the phenomenon, characterizing and understanding the effect of short time heat treatment and preceding plastic deformation on the mechanical properties of cast iron are important.

Blast cleaning, an industrial process for effective removal of cast residues, can be viewed as an un-controlled version of shot peening. Depending on blasting parameters used, the resulting residual stresses and surface roughness vary significantly. The effect of the clean blasting processes at the foundries at Scania and Volvo on the fatigue strength of cast iron has previously not been properly quantified. However, previous work on blasted component from the production line at Volvo revealed severe surface damage resembling a heavily shot peened surface. Such damage may lead to markedly reduced fatigue strength of the component as shown by the results from the heavily peened LGI. By a proper selection of the parameters, the blast cleaning process could be improved to result in a better surface quality and beneficial residual stress state on the components. Similar to shot peening of cast irons, very little information can be found in the open literature on the effect of blast cleaning process.

Compressive residual stresses contribute to improved fatigue resistance only when they remain stable during cyclic loading. Therefore, knowledge of the stability of compressive residual stresses is important for understanding the influence of surface treatments and improving their efficiency. In Part I, the benefit of gentle shot peening on the fatigue strength of CGI vanished after annealing at 100°C for 100 hours. The effect of time and temperature on residual stresses and further on fatigue strength should therefore be studied more thoroughly.

The widely used X-ray diffractometry (XRD) and other diffraction based techniques for residual stress analysis are based on measuring elastic strains, from which residual stresses are derived through the use of elastic models and so called X-ray elastic constants (XECs). During the course of Part I, it was found that default device XECs are used for residual stress analysis of cast irons by different laboratories. A few calibration tests carried out following a standard procedure showed XECs varying with cast irons and loading condition. The loading condition dependence of XECs of a grey cast iron under 4-point

[1]V.L. Richards, T.V. Anish, S. Lekakh, D.C. Van Aken, Age Strengthening of Gray Iron-Kinetics Study, International Journal of Metalcasting. 2 (2007) 7-16

bending tests was reported by German researchers[2], who attributed it to the different behavior of ferrite and graphite under tension and compression. Stress distributions in such materials with a heterogeneous microstructure are complicated. Obviously, the applicability of the international standard on cast irons needs further investigation.

Based on the above issues, central research questions were formulated as main objectives for Part II and 6 project tasks were designed to provide answers to these questions.

3. Objective

The ultimate objective of the project is to increase the fatigue strength of cast iron components through the use of surface mechanical treatments to optimize residual stresses. Main goals set-up for Part II are to

- Increase the fatigue strength of grey cast iron by 15% and that of CGI by 30% through surface treatments and short time annealing
- Identify a critical service temperature for shot peened cast components
- Quantify the effect of current clean blasting process on fatigue strength and suggest improved process
- Complete one PhD thesis with additional 3-5 scientific publications

4. Project realization

The project has been carried out through collaborations between the Division of Engineering Materials of Linköping University, Volvo Group Trucks Technology and Scania CV AB. Part II was planned for the period April 2014-March 2016. Shortly before starting, the PhD student working in Part I went on sick leave and did not formally return to the project. The project work that LiU was responsible for was therefore carried out partly by a dedicated postdoc Belkiri Kaouache (13 months) and partly by Ass. Prof. Ru Lin Peng. The project period was also extended to September 2016, upon agreement of all partners and approval by Vinnova. The working group consists of the abovementioned persons and representatives from Volvo (Dr Maqsood Ahmad) and Scania (Dr Taina Vuoristo, Dr Daniel Bäckström, Dr Mathias König and Dr Jessica Elfsberg).

Three cast irons, one grey cast iron from Vovlo (Volvo LGI), one grey cast iron from Scania (Scania LGI), and one compacted graphite iron from Scania (Scania CGI), were included for study in Part II. Volvo LGI and Scania CGI have an essential pearlitic matrix while Scania LGI has a pearlitic-ferritic matrix. Specially designed plates were cast and used for fatigue testing in the project.

[2]V. Hauk, U. Wolfstieg, Röntgenographische Elastizitätskonstanten, HTM-Journal of Heat Treatment and Materials, 31 (1976) 38-42.

Bending fatigue testing is used to evaluate the effect of the different processes, including shot peening, blast cleaning and heat treatments. The bending fatigue tests were carried out in the material lab in Volvo and Scania.

Characterization of the blast cleaning processes and preparation of blast cleaned specimens for the fatigue tests were performed in the foundry of Volvo and Scania. The blast cleaning was carried out on the production line of Volvo and Scania. Special holders/fixtures were used to allow cast plates to be blast cleaned and blasting intensity recorded in the same facility and under the same condition as real components.

Extensive heat treatments and microhardness tests were performed to determine the optimal heat treatment for strengthening. To understand the mechanism of strengthening by short time heat treatments, microstructural study in both SEM and Transmission Electron Microscope (TEM) was carried out on specimens in different conditions at LiU.

Cross-sections of surface treated specimens were prepared for characterization of changes/damage in the form of plastic deformation and microcracking in Scanning Electron Microscope (SEM). Residual stress profiles were obtained by the X-Ray diffraction (XRD) technique in combination with step wise layer removal by electrolytic polishing. Calibration measurements of XEC were made on the LGI and CGI used in the project. To evaluate the effect of graphite morphology, a ferritic spheroidal graphite cast iron was also included. Specially designed portable tensile rig and 4-point bending rig were used to apply the desired load on the test specimens during XRD measurement. The SEM and XRD experiments were performed in the Engineering Materials lab at LiU.

5. Results and deliverables

5.1 Delivery to FFI-goals

The project has in a number of ways contributed to the goals of both the FFI program "*Vehicle Development*" and the subprogram "*Materials for More Effective Vehicles*". The project has led to a close and productive collaboration between the Division of Engineering Materials at LiU, Scania CV AB and Volvo Group Trucks Technology. The collaboration strengthens the research and innovation capacity in Sweden and contributes to the objective to secure competitiveness and employment.

Eventual implementation of the project results also contributes to goals of the subprogram. The project work showed that fatigue properties can be greatly enhanced through proper surface mechanical treatments. LGI is a rather inexpensive material, and with surface mechanical treatment costly changes of material can be avoided and the loading range of the components manufactured of cast iron increased. In particular, cleaning of castings and surface strengthening can be done in one and the same process, which means improved part qualities without additional process step. Thus, the two goals, substantial cost reduction and significantly better material properties, can be fulfilled using the methods studied in this project.

5.2 Main Project Results

5.2.1 Achievement of Project Goals in Part II

Improvements in fatigue strength obtained by the different treatments investigated in Part II are summarized in Fig. 1. The blast cleaning processes which are similar to heavy shot peening greatly increased the bending fatigue limit of LGI and CGI, with up to 75% gain.

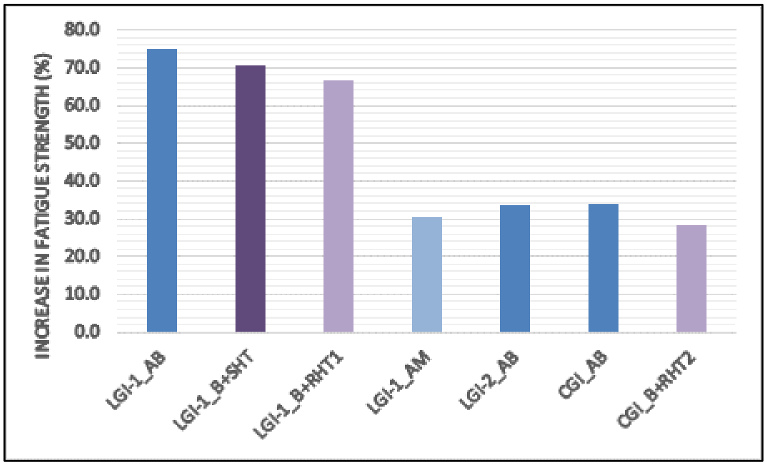

Figure 1. Improvement in fatigue limit after the different treatments. AB: as blasted, AM: as machined, B+SHT: blasting + annealing 20 min at 285 °C, RHT1: blasting + annealing 300 h at 120 °C, RHT2: blasting + annealing 300 h at 220 °C.

Optimal strengthening heat treatment was found to be 285 °C and 20 to 30 minutes for heavily shot-peened LGI and CGI. However, it did not further improve the bending fatigue limit. Instead, the gain from blasting was slightly lowered, from 75% to about 71%.

A long term exposure at 120 °C reduced the benefit of blasting from 75% to about 67% for Volvo LGI and a similar exposure but to 220 °C decreased the gain from 34 to 28% for Scania CGI. Keeping the service temperature below 120 °C for Volvo blasted LGI and below 220 °C for Scania CGI retained more than 80% of the gain from blasting.

Three conference papers have been published and three more conference/journal papers are under preparation. Due to sick leave of the PhD student, no PhD thesis was delivered.

The following subsections give a more detailed presentation of the main project results.

5.2.2 Effect of Blast Cleaning Processes on Castings Surface and Fatigue

The blasting intensity measured in different positions and different times ranged from 0.164 to 0.198 mmC and 0.314 to 0.332 mmC for Volvo's and Scania's process, respectively.

The casting skin was typically 0.3 to 0.5 mm thick. Both mould residues and outer surface oxide scale of castings were completely removed by the cleaning processes, see the SEM-cross section images in Fig.2. Somewhat different microstructures were revealed: Scania's casting skins were densely populated by long, thin graphite inclusions while such inclusions were few in Volvo's casting skins. More severe surface distortion was also observed in Scania's specimens. In addition, the high blast intensity in combination with the high density of graphite inclusions resulted in more extensive microcracking in surface regions with massive reoriented graphite inclusions.

Although the blast intensity for Volvo LGI is similar to the intensity of the heavy shot peening employed on machined LGI in Part I, surface damage in the form of distortion and microcracking was much lower in blasted castings (Fig. 2). The casting skin in Volvo LGI is believed to have played an important role here. Damping from the outer oxide scale in a casting skin and the ductile subsurface layer of a ferritic-pearlic matrix with few graphite inclusions greatly reduced the surface deformation and microcracking.

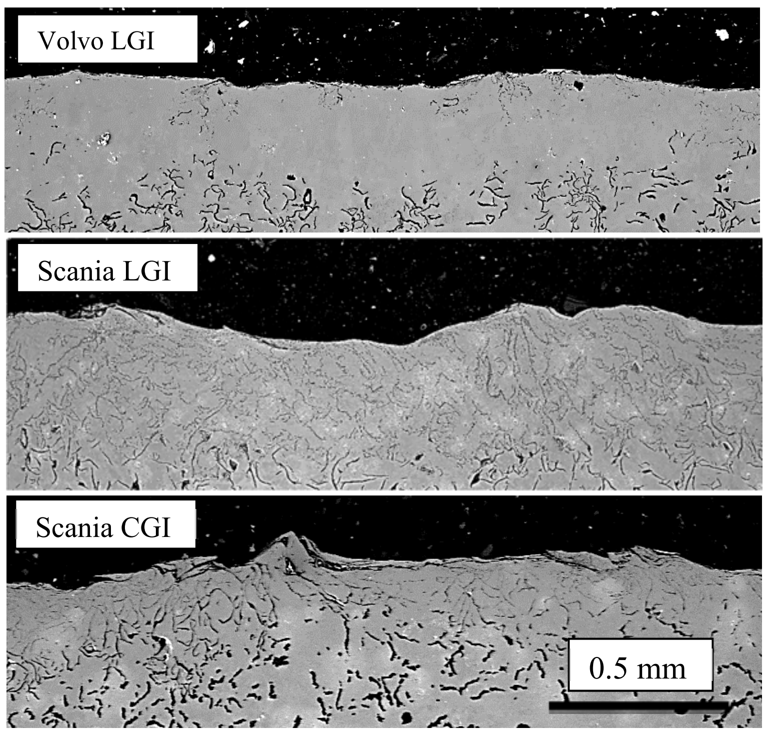

Figure 2. Cross-section of blast cleaned LGI and CGI showing casting skins.

The blast cleaning operations generated plastic deformation to a large depth, at least 500 µm in Volvo LGI and 900 µm in Scania CGI, as indicated by the measured diffraction peak width (FWHM) shown in Fig. 3. Accordingly, compressive residual stresses were induced in a large surface layer, 800 µm in Volvo LGI but much deeper in Scania CGI, 1200 µm. This is attributed to the much higher blasting intensity but also that CGI responds better to peening as observed in Part I. On the other hand, the surface compressive residual stresses are much lower, about -75 MPa in CGI, contrasting -300 MPa in LGI. The microcracking and high surface roughness explain the low surface residual stresses in blast cleaned CGI.

S-N curves from fatigue tests are presented in Fig. 4 and 5 and the derived fatigue limits are given in Table 1. The casting skin in Volvo LGI is detrimental to fatigue resistance. About 31% gain in fatigue limit was achieved when the layer was machined away. The blast cleaning more effectively increased the fatigue resistance through removal of the outer oxide scale, strengthening of the soft casting skin and especially introducing of compressive residual stresses to a large depth. A 75% increase in fatigue limit was obtained and fatigue strength in the slope region of the S-N curve was greatly enhanced.

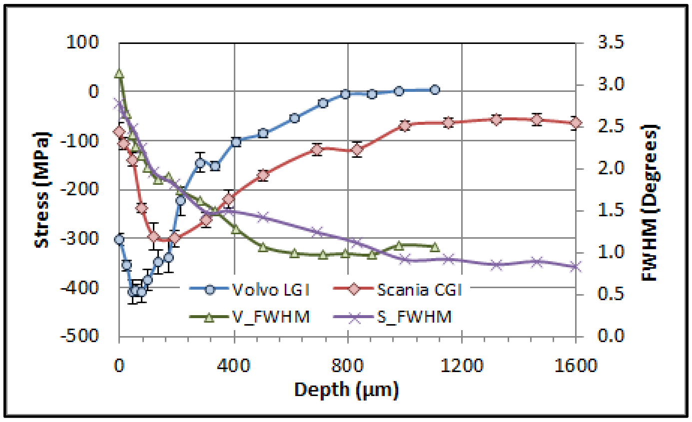

Figure 3. Residual stress and FWHM profiles in blasted LGI and CGI. XEC=5.81×10^{-6} MPa^{-1}

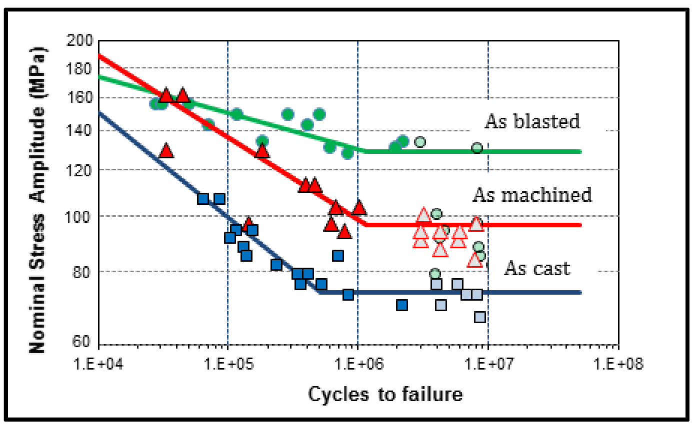

Figure 4. S-N curves for Volvo LGI. Stress ratio R ratio =0.1, runouts: over 3×10^6 cycles.

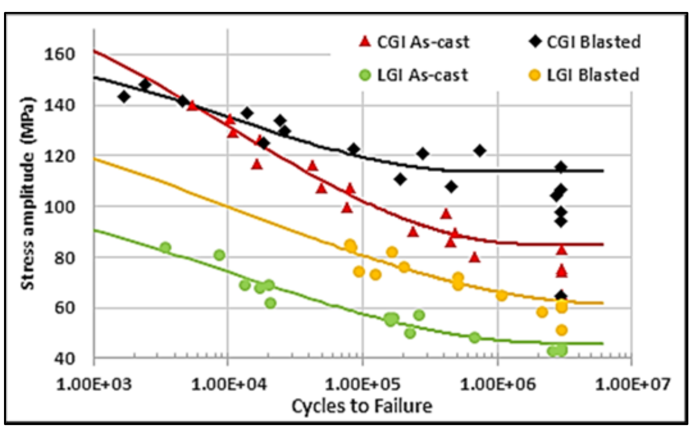

Figure 5. S-N curves for Scania CGI and LGI, in as cast and as blasted conditions. Stress ratio R ratio= ~0.15, runouts: over 3×10^6 cycles.

The Scania blast cleaning process also gave better fatigue strength, the increase was, however, much lower, about 34% in fatigue limit for both the LGI and CGI (Fig. 5 and Table 1). The lower compressive stresses (Fig. 3) and the more severe damage in the surface could explain the large difference between the Volvo and Scania specimens. This indicates the potential for optimization of Scania's current blast cleaning process to improve the fatigue resistance of castings.

It can be concluded that with regard to enhancing fatigue resistance of castings, Volvo's blast cleaning process is very effective while Scania's blast cleaning process has the potential for optimization. As up to 75% improvement can be achieved by using suitable blast cleaning parameters, there is no need for the application of other surface treatment methods like deep rolling or vibropeening.

Table 1 Fatigue limit in MPa and its increase by surface treatment

	Volvo LGI	Volvo LGI	Scania LGI	Scania CGI
As cast	73.8±5.7	73.8±5.7	46±4	85±5
Machining		96.4±6.4		
Blast cleaning	129.1±3.9		62±4	114±6
Change in %	74.8	30.6	34.8	34.1

5.2.3 Critical Service Temperature and Effect of Heat Treatments on Fatigue

The blast cleaning process can be considered as the application of shot peening to remove residues from castings. Therefore, when a significant improvement in fatigue performance was revealed for the blast cleaned LGI and CGI, it was decided that the study on the effect of service temperature should be carried out on the blast cleaned specimens. Long term heat treatment to simulate the effect of temperature in the cooling channels and the maximum temperature of the cylinder head were performed on Volvo LGI and Scania CGI, respectively. As shown in Fig. 6-7 and Table 2, annealing for 300 h at 120 ºC lowered the fatigue limit by 5% for Volvo blasted LGI and annealing for 300 h at 220 ºC caused a 4% reduction in Scania blasted CGI. XRD measurements showed partial relaxation of the beneficial compressive residual stresses after the annealing treatments, which explained the negative effects on the fatigue performance. Nevertheless, the fatigue limits remained much better than the as cast condition, about 67% for Volvo LGI and 28% for Scania CGI.

Table 2 Fatigue limits (in MPa) after different heat treatments

	Volvo LGI	Volvo LGI	Scania CGI
Strengthening annealing	125.8±2.4		109±4
Relaxation annealing		123.0±2.4	
Compared with blasted (%)	-2.6	-4.7	-4.4
Compared with as cast (%)	70.5	66.7	28.2

The strengthening annealing (Section 5.2.4) was applied on Volvo blasted LGI, however, no expected beneficial effect was found. Instead the fatigue limit was slightly decreased by about 3%. The benefit from the strengthening seems to be offset by the negative effect from relaxation of the surface compressive residual stresses to about -180 MPa.

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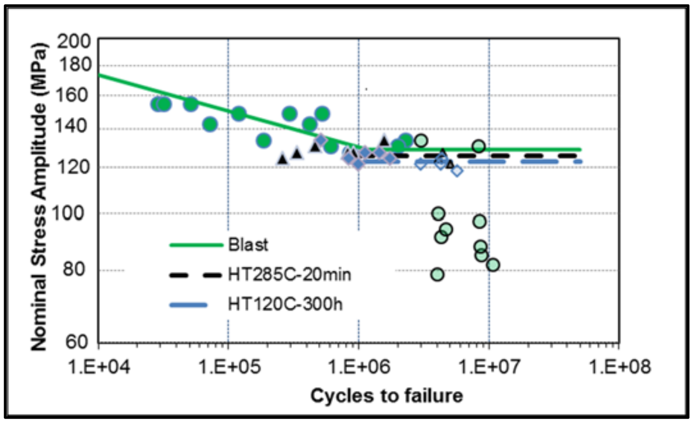

Figure 6 The effect of heat treatments on Volvo blasted LGI. R ratio=0.1, runouts: over 3×10^6 cycles.

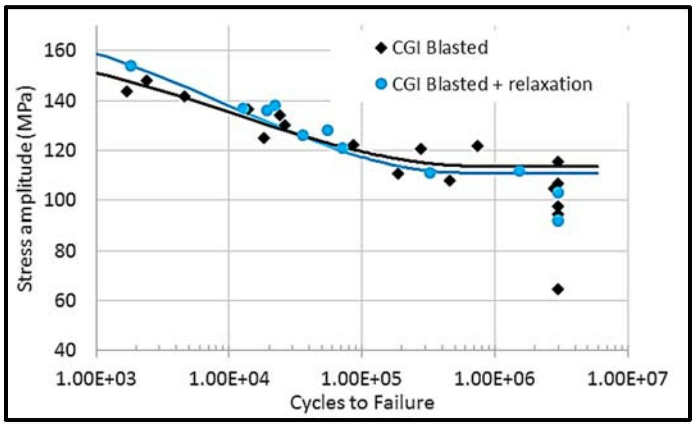

Figure 7 The effect of stress relaxation annealing (300 h at 220 °C) on Scania blasted CGI. R ratio=~0.15, Runouts: over 3×10^6 cycles.

5.2.4 Optimal Heat Treatment for Strengthening of Shot Peened Cast Irons

Extensive heat treatments with varied time and temperature performed on LGI and CGI with and without shot peening showed that annealing at 285 °C for relatively short time, about 20 to 30 minutes gave the best strengthening effect. Tensile tests also revealed that the optimal heat treatment resulted in an obvious increase in strength in machined + shot peened specimens but not in machined specimens.

While the strengthening effect by short time annealing observed in Part I was confirmed and the parameters for optimal strengthening was determined, microstructure studies by transmission electron microscope to explore the mechanism behind is less successful. 20 nm precipitates were observed in non-shot peened specimen but few in the shot peened affected zone. After the annealing, 5 to 10 nm precipitates appeared in the shot peened specimens. The strengthening effect could be related to re-precipitation of the fine particles.

5.2.5 XEC for residual stress measurements

XEC determined from the in situ XRD measurements are summarized in Table 3. The XEC for steel from the literature is given in the last column as reference. It should be noted that residual stresses are normally measured in the matrix phase which is the ferrite phase in steels and cast irons. It can be seen that the ferritic spheroidal cast iron has an XEC closest to the reference value. The spherical graphite seems to have a minor effect on the XEC. Both LGI and CGI show somewhat lower XEC, indicating the influence of the elongated graphite inclusions in the material. On the other hand, the effect of loading anisotropy common for LGI is not obvious, as the 4-point bending in tension and compression gave essentially same XEC. One explanation could be that the calibration measurements had to be performed at a relatively low elastic loading range and the measurements were less sensitive to the anisotropic loading. Residual stresses calculated using the reference XEC are about 13% lower for the LGI (lowest 5.11) and 10% lower for the CGI (lowest 5.28).

Table 3 Effective XEC (10^{-6} MPa^{-1}) for pearlitic LGI, pearlitic CGI and ferritic SGI

Test method	LGI	CGI	FSGI	Reference
Uniaxial Tension	5.13±0.01	5.28±0.01	5.76±0.03	5.81
Four-point Tension	5.11±0.03	5.50±0.02	-	5.81
Four-point Compression	5.22±0.03	5.40±0.01	5.31±0.01	5.81

6. Dissemination and publications

6.1 Knowledge and results dissemination

Parts of project results have been presented in international conferences. 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.

The project work has resulted in increased understanding of the effects of surface mechanical treatments on fatigue performance of grey and compacted graphite cast irons. The benefit and possibility to use blast cleaning process to achieve desired fatigue properties are recognized. Critical service temperatures are identified for blast cleaned components which also are applicable for heavy shot peened castings. The knowledge generated from the project is going to be used for product development projects and implementation may eventually be done to optimize current production process.

6.2 Publications

1. M. Ahmad, R. Lin Peng, M. König, D. Bäckström, Sten Johansson. ”Fatigue of Blast Cleaned Grey Cast Iron”. 10th International Conference on Residual Stresses, Sydney, 3-7 July, 2016.
2. B Kaouache, D Bäckström, M Ahmad, T Vuoristo, S Johansson and R L Peng: “To Increase Fatigue Strength of Grey Iron By Shot Peening”, 4th International Conference of Engineering Against Failure, 24-26 June 2015, Skiathos, Greece.

3. R L Peng, T Vuoristo, D Bäckström, M Ahmad, M Lundberg and S Johansson: "Fatigue Strength of Shot Peened Compacteded Graphite Iron", 12th International Conference on Shot Peening in Goslar, Germany, 15-18 September, 2014.
4. M. Lundberg et al. “Effective X-Ray Elastic Constant for Residual Stress Measurements in Cast Iron”, Manuscript under preparation.
5. R. Lin Peng, M. König, M. Ahmad, J. Elfsberg, S. Johansson: “The Influence of Blast cleaning on the Fatigue Behavior of a Compacted Graphite Iron”, Planned manuscript for EuroMat 2017.
6. R. Lin Peng, M. König, M. Ahmad, J. Elfsberg, S. Johansson:“Fatigue Behavior of Surface Mechanically Treated Cast Irons at Elevated Temperatures”, Manuscript to be prepared.

7. Conclusions and future research

Main conclusions from the project work are summarized below.

- The project work has demonstrated that the fatigue strength of LGI and CGI can be greatly enhanced by shot peening/blast cleaning. Up to 75% increase in fatigue limit can be obtained on castings. Therefore, no alternative surface mechanical treatments need to be considered in the project.
- By the use of proper process parameters, cleaning and strengthening against fatigue can be achieved using one and the same blasting process.
- Selection of process parameters for blast cleaning/shot peening, especially the intensity of impact, is crucial and needs to take into consideration of the microstructure in the surface layer. It can be derived from work in Part I and II that lower peening intensity should be used on machined components to avoid severe surface damage, while much higher peening/blasting intensity can and should be used on components with a casting skin.
- The blast cleaning process currently running on Volvo’s production line seems to be optimal, showing an improvement by 75% in fatigue limit, while the process in Scania, giving 34% increase, may be optimized by for example, lowing the blast intensity.
- The critical service temperature for the use of shot peened/blasted LGI and CGI seems to depend on the treatment parameter, type of fatigue loading and likely material. For gentle shot peening, its benefit for axial fatigue loading disappeared already at 100 ^{o}C (result from Part I). For blasting (equivalent to heavily shot-peening), more than 80% of the improvement in resistance to bending fatigue was retained after long time annealing of Volvo blasted LGI at 120 ^{o}C and Scania blasted CGI at 220 ^{o}C. In comparison with the as cast condition, the fatigue limit was still 67% better for Volvo LGI and 28% better for Scania CGI.
- Annealing parameters for optimal strengthening heat treatment were found to be 285 ^{o}C and 20 to 30 minutes for heavily shot-peened LGI and CGI. While the

heat treatment was found to increase axial fatigue strength (result from Part I), it has no beneficial effect on bending fatigue.

- Compressive residual stresses generated from shot peening/blast cleaning and hardening of the casting skin are the main reason for the increased fatigue resistance. Partial relaxation of the compressive residual stresses during the different annealing treatments resulted in reduced benefit from the surface mechanical treatment.
- The X-Ray elastic constant (XEC) for residual stress analysis varies with the microstructure. The use of the literature XEC for the ferrite phase may cause certain errors, 13% lower in stress for the LGI and 10% lower for the CGI.

The project work has resulted in increased understanding of the complex relationship between surface mechanical treatments and fatigue behavior of LGI and CGI. Because of the inhomogeneous microstructure of both types of cast irons with elongated graphite inclusions as well as the existence of casting skin in cast components, response of the cast irons to surface mechanical treatments varies largely. Depending on the process parameters and microstructure in the component surface, the treatment may be more or less efficient and even negative results (Part I) can be obtained. Further research work is needed to study closely the influence of surface microstructure, such as machined or as cast, as cast with different characteristics of casting skins, and properties such as ductility and hardness in selection of shot peening/blast cleaning processes. In addition, a more systematic study of residual stress relaxation at elevated temperature is also required as it was revealed that the stability of the beneficial residual stresses at service temperature seems to vary depending on the peening intensity and material.

Specimens used in the project are from specially cast plates. Microstructures/surface conditions in the casting skin may deviate from those in the cooling channels of cylinder heads. Further, the blast cleaning process used by Scania in the current project is for engine blocks. As cylinder heads are the target component, the findings should be checked for their applicability to cylinder heads.

8. Participating parties and contact person

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