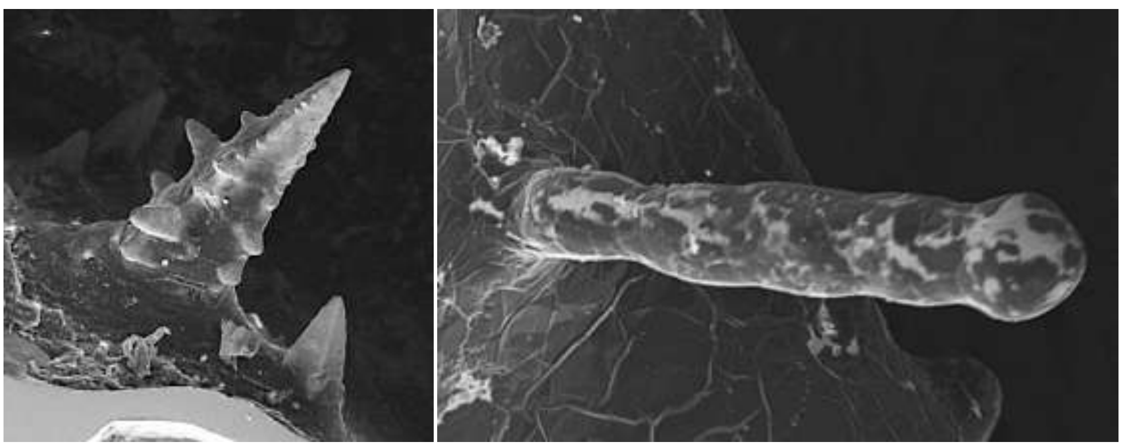
SPOFIC
Shrinkage Porosity Formation in Compacted Graphite Iron



Project within Vehicle development

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FFI

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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

The project SPOFIC, Shrinkage Porosity Formation in Compacted Graphite Iron, has been executed in cooperation between Swerea Swecast, Nya Arvika Gjuteri AB, Scania CV AB samt Volvo Powertrain AB from 2011-03-01 to 2014-09-30. At the project start, the key competence Attila Diószegi was active at KTH, but during the period he got more involved at Tekniska Högskolan i Jönköping AB, JTH. Parts of the work planned to be performed at KTH has therefore been moved to JTH.

The usage of compacted graphite iron (CGI) in strategically important engine parts has increased considerably the last decade, mainly because of stricter legislations concerning emissions from heavy duty vehicles which requires higher combustion pressures and therefore higher loads on the material.

Compacted graphite iron is more prone to pore formation than the conventionally used gray iron. Elimination of the pores is only possible by knowledge of the formation mechanisms and influencing parameters. The industrial partners are not satisfied with an increased understanding of formation mechanisms, but also requires a possibility to predict and control the pore formation risk for each melt. This will result not only in a improved material quality, but also in less rejections.

The overall aim of the project was to **develop methods for controlling and testing for CGI-components without porosities.** This was divided into six intermediate goals:

- Root causes for pore formation
- Sample geometry for provoking pore formation
- Identification och quantification of parameters influencing pore formation
- Evaluation of non-destructive testing methods for pores in CGI-castings
- Method for manufacturing of compacted graphite iron in laboratory scale
- Development of a method for combined thermal and volume change analysis

All the intermediate goals are at least partly fulfilled. Difficulties regarding sample geometry for provoking pore formation led to that the evaluation of non-destructive testing has begun but not can be considered as finished. To summarise, the project has created a good understanding of parameters to be considered in a controlling method. Some work still needs to be done before an equipment can be realized.

The project has successfully contributed to future competetiveness of the swedish heavy duty vehicle producers through a potentially higher materials quality, building up / maintenance of a strong academic environment and a fruitful collaboration between academy, institute and industry.

Within the project the following academic theses has been published:

Licentiate thesis by Sadaf Vazehrad 2014
Master thesis by Dimitrios Siafakas 2012
Master thesis by Sadaf Vazehrad 2011

The most important observations and conclusions from the project are:

- Gas pores forms from melt or at the earliest stage of solidification, Figure 3.
- There are two types shrinkage pores, those containing fine, regular shaped dendrites and those with more coarse dendrites with fully or partly extinguished secondary dendrite arms, Figure 3.
- Higher count of smaller sized eutectic colonies leads to more solidification shrinkage.
- The level of gas forming elements, as hydrogen and nitrogen, increases in the melt during mould filling, Figure 1. Observations imply that gas forming elements co-operate with soldification and cooling shrinkage at pore formation.
- Increased nodularity (%spherical graphite particles) increases the tendency for pore formation.
- Shrinkage pores with an internal surface graphite film has been formed without contact with the surroundning atmosphere.
- Colour etching and EPMA-analysis show two colonies of grafite nodules, with or without austenite edge. Those with the austenite edge has been formed eutectically while those, much smaller ones, without the edge was formed from the last solidifiying melt, Figure 2.
- EPMA-analysis shows higher concentrations of sulphur and manganese and magnesium in contact with graphite particles. This indicates that the graphite in grey cast iron nucleates on MnS whilst CGI nucleates on MgS.

2. Background

The background to the project as described in the application documents:

”Striving for less environmental impact, road transports need to improve its energy efficiency at the same time as the emissions of undesired residues must decrease. This is reflected in future stricter legislations concerning the automotive industry, e.g. Euro 6 and 7. Furthermore, energy efficiency is a very strong competitive mean for swedish heavy duty vehicle manufacturers aiming for a larger global market shares. Fuels are responsible for about one third of the total cost during the full lifelength of a truck. One important parameter for reaching the environmental goals is an increased combustion pressure. The higher pressure will require stronger cylinder blocks and heads. Larger dimensions of the components are not an option since the weight the will increase which will cause a higher fuel consumption. A better solution is to choose a stronger material than grey cast iron.

Compacted graphite iron (CGI) has the last decades been found to be a useful stronger alternative material. There are a handful of commercially available controlling systems for achieving a high quality production of this difficult material. Scania as well as Volvo have small series of high effect engine blocks by CGI. Unfortunately, the CGI-material is more prone for shrinkage pore formation. The common methods only takes the graphite particle shape into consideration. As the solidifying metal shrinks at the casting process, pores are formed in the component. This type of defects are usually discovered late in the manufacturing chain, or in worst case through leakage or poor strength in the final product at the customer. Besides large costs, both economically and regarding customer confidence, the defects also causes larger environmental impact due to emissions from the casting process as well as residues that cannot be reused. Production that results in rejection will not enhance fulfillment of the objective of the environmental focused work.

As the volume of compacted graphite iron increase, the problem must be focused. The future success of the Swedish heavy automotive industry depends on the development methods for efficient production of defect free CGI components. The world leading position , both technically and commercially, may thus be maintained. The two strongest truck engines in the world are from Volvo and Scania respectively. Additionally, Swedish engines are known to be fuel-efficient. The project will help us to both increase the productivity and at the same time decrease the environmental impact from the manufacturing through less rejections and even more efficient engines.”

An faster increase of the CGI-volume than predicted in 2011 accents the problems even further.

3. Objective

The objective of the project is to in the long run facilitate manufacturing of CGI without macro pores. The means to achieve this are building knowledge about formation mechanisms and quantification of influencing parameters.

4. Project realization

The project was divided into six parts (A-F):

Part A

CGI components with shrinkage pores are collected from the participating companies. To identify the dominating phenomena at pore formation, the parts with pores will be compared with the same components without shrinkage pore defects. The typical positions of the pores will also be monitored.

Activities:
A1. Literature survey regarding solidification mechanisms and shrinkage pore formation in CGI.
A2. Decision about which components the rpoject should investigate and delivery of those from the companies.
A3. Investigation and identification of the main reasons for pore formation. Studies will be performed by Light Optical Microscoping on unetched and colour etched samples and by using the SEM for exploring the interior of the pores.

Milestone: Analysis of the reasons for shrinkage pore formation.

Delivery: Report

Part B
Design of simplified sample geometries that at production conditions will promote shrinkage pore formation. The geometry will be based on the results from part A and on the expert knowledge at the participating companies. The reason for developing a separate sample geometry is that the handling of the samples will get much easier.

Activities:
B1. Identify geometrical conditions promoting shrinkage pore formation in CGI.
B2. Simulation.
B3. Design of sample with pore promoting geometry.
B4. Model manufacturing.
B5. Verification of sample geometry.

Mile stone: Manufacturing of sample model.

Delivery: Reports and sample model.

Part C
Experimental castings of the sample geometry developed in part B to identify the most important parameters for shrinkage pore formation.

Activities:
C1. Foundry experiments with varying values of important parameters.

C2. Development of feeder aiming for obstructing the formation of shrinkage pores.
C3. Evaluation of how different parameters influence the pore formation. Investigations using light optical microscope on unetched and colour etched samples as well as SEM on the interior of the pores we be performed.

Mile stone: Quantification of the influence of the studied parameters.

Delivery: Reports.

Part D

Evaluation of known non-destructive testing (NDT) methods potential of reveal the risk for pore formation in CGI. The evaluations will be performed on the samples cast from part C.

Activities:
D1. Resonance frequency method.
D2. Ultrasonic techniques.
D3. Identification of other potential methods.

Mile stone: Evaluation of NDT-techniques.

Delivery: Reports.

Part E

Carefully controlled laboratory scale experiments aiming for investigate the solidification mechanism of CGI, i.e. the growth of eutectic cells connected to primary austenite. The results is to be compared with the behavior of grey cast iron and ductile cast iron.

Activities:

E1. Development of a method for laboratory scale manufacturing of CGI. Remelting CGI will cause fading of the effect of the modification of the graphite shape. This means that a remelted CGI-sample may solidify as a grey cast iron. The present equipment needs to be redesigned for a successful production of CGI.
E2. Experimental series where the cooling rate and the carbon content are quenched at different stages of the solidificaiton.
E3. Micro structural investigations of the material produced in E2.

Mile stone: Characterisation of graphite growth in CGI.

Delivery: Method for laboratory scale production of CGI and reports.

Part F
Treatment strategies of melts intended for CGI production are based on interpretations of cooling curves of specially designed samples. The controlling techniques are intended to be further elaborated for combining the thermal analysis with recording of density variations (and/or other phenomenon) and thereby facilitate the prediction of the risk for pore formation for every melt.

Activities:
F1. Development of a analysis method combining cooling curves with recording of density variations and/or other phenomenon connected to solidification.
F2. Casting experiments using the method from F1 for variations of the parameters with the aim to control the formation of shrinkage pores.
F3. Evaluation of the experiments. Micro structural investigations and analysis of the measured temperature and density variations.

Mile stone: Development of analysis method.

Delivery: Analysis method for indication pore risk of each melt intended for CGI casting and reports.

Part A was performed as a Master thesis at KTH, Vazehrad 2012. Scania CV AB och Volvo Powertrain AB contributed with CGI components. In addition, an investigation of the behavior of gas forming elements in CGI melts was performed in another master thesis, Siafakas 2013, in collaboration between KTH and Volvo Powertrain AB. Part B has been executed by KTH, Swerea Swecast and Volvo Powertrain AB. Part C was done by Swerea Swecast AB and Scania CV AB. Part D is performed by Swerea Swecast while part E and F have been outsourced to Tekniska Högskolan i Jönköping AB from KTH. Nya Arvika Gjuteri AB contributed with the raw material for parts E and F.

5. Results and deliverables

5.1 Delivery to FFI-goals

The programme description (Swedish edition 05-05-2009 10:35) for vehicle development states the following goals:

- Through increased research and innovation capacity in Sweden, the competitiveness and jobs of the Swedish heavy automotive industry will be ensured, on short time basis and preferably also in the long run.

- Develop internationally connected and competitive research and innovation environments, in who academy, institutes and industry collaborates.

- Promote international research- and innovation activities where conditions for participations in the EU Framework Programme for Research and Innovation as well as other international research collaboration is assessed.

The programme ”Vehicle development” covers five subareas. SPOFIC addresses “Material Technology for efficient vehicles” for which the following is stated:

Vision: New materials technology meeting the long term requirements from the market concerning vehicle structure and harsch environments.
Goal: TR with substantial weight reduction and/or cost reduction and/or improved material quality
Criterias: Adapted for market. Competitiveness. Innovation. Efficiency. Safety. Sustainability. Environment oriented.

The project SPOFIC has contributed to **increased research capacity** in Sweden as well as to the **collaboration** between automotive industry, institute and academy. The technical progress contributes to a maintained or improved **competetiveness** for the heavy automotive in Sweden. The research results has been presented at international conferences and been published in peer-reviewed international journals, i.e. **independent quality review**. The technical progress will mainly contribute to **improved materials quality**. In the long run, the improved material may enable **weight reduction** in components and furthermore, a better process understanding may decrease rejection, i.e. **decrease the environmental impact**. The CGI-production could also be done at decreased costs. The majority of CGI production is currently done in the automotive industry, but **other industry** as for example ductile iron foundries may use both methods and results from the project.

5.2 Delivery to project goals

The overall goal of the project is to develop control and test methods for production of CGI components without pore defects. This overall goal is divided into six sub goals:

- Root causes for pore formation
- Sample geometry for provoking pore formation
- Identification and quantification of parameters influencing pore formation
- Evaluation of non-destructive testing methods for pores in CGI-castings
- Method for manufacturing of compacted graphite iron in laboratory scale
- Development of a method for combined thermal and volume change analysis

To summarize, the project has created a deep understanding of which parameters to base a control method upon. However, some practical work is left before a robust equipment may be realized.

Root causes for pore formation in compacted graphite iron are combined physical phenomenon. Solidified iron has a higher density than liquid iron and the solubility of gas forming elements is lower in solid state than in liquid state. The design of the components determines if the density difference between solid and liquid, i.e. solidification shrinkage, will create pores. The properties of the mould material will, together with design of mould and cores, determines if evolved gases causes problems. Other requirements on the component tends to make optimization concerning shrinkage and gas pores impossible. The project has clearly shown that gas forming elements in the raw material will increase the risk for pore formation considerably. **The sample geometry for provoking pore formation** was harder than predicted to achieve. A number of failures were done before a successful experiment during 2014. **Identification and quantification of parameters influencing pore formation** has been started and besides critical levels of gas forming elements, important structure parameters, such as double populations of nodules and segregation patterns has been observed. **Evaluation of non-destructive testing methods** for pores in CGI components is, due to the difficulties with the sample geometry, delayed. The work has started, but cannot be described as finished. The development of a **method for manufacturing CGI in a laboratory scale** has been successful with several trials resulting in CGI. The development of a combined method for thermal analysis and volume changes has also been fairly successful. The method can be considered as finalized, but some work is needed before an actual equipment may be realized.

6. Dissemination and publications

6.1 Knowledge and results dissemination

There are a great interest from the industrial partners to take part of the results from the project. The continuation project SPOFIC II started in January 2014 with the following participants: Scania CV AB, Volvo Powertrain AB, Swerea Swecast, Tekniska Högskolan i Jönköping AB and SinterCast AB. Four Ph.D.-students, one postdoc and one professor is fully or partly financed by the project. Within this forum, the results from SPOFIC I are frequently discussed.

6.2 Publications

Vazehrad ”Shrinkage Porosity Characterization in Compacted Cast Iron Components”, Master Thesis, KTH 2012.

Siafakas ”Investigation of Hydrogen and Nitrogen Content in Compacted Graphite Iron Production”, Master Thesis, KTH 2013.

Vazehrad “A Study On Factor Influencing the Microstructure and Shrinkage Porosity Formation in Compacted Graphite Iron”, Licentiate thesis, KTH 2014.

Vazehrad, Elfsberg, Diószegi ”On factors influencing macro shrinkage porosity formation in compacted graphite iron”, Materials Science Forum, Vol. 790-791, (2014), pp. 429-434.

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Vazehrad, Elfsberg, Diószegi ”Study of microstructure in cast iron using colour etching and electron microprobe analysis”, accepterad för publicering av International Journal of Materials Characterization.

Vazehrad, Diószegi “Elemental segregation pattern in lamellar and compacted graphite iron”, KTH, 2014.

7. Conclusions and future research

Conclusions from the project:

- Gas pores forms from melt or at the earliest stage of solidification, Figure 3.
- There are two types shrinkage pores, those containing fine, regular shaped dendrites and those with more coarse dendrites with fully or partly extinguished secondary dendrite arms, Figure 3.
- Higher count of smaller sized eutectic colonies leads to more solidification shrinkage.
- The level of gas forming elements, as hydrogen and nitrogen, increases in the melt during mould filling, Figure 1. Observations imply that gas forming elements co-operate with soldification and cooling shrinkage at pore formation.
- Increased nodularity (%spherical graphite particles) increases the tendency for pore formation.
- Shrinkage pores with an internal surface graphite film has been formed without contact with the surroundning atmosphere.
- Colour etching and EPMA-analysis show two colonies of grafite nodules, with or without austenite edge. Those with the austenite edge has been formed eutectically while those, much smaller ones, without the edge was formed from the last solidifiying melt, Figure 2.
- EPMA-analysis shows higher concentrations of sulphur and manganese and magnesium in contact with graphite particles. This indicates that the graphite in grey cast iron nucleates on MnS whilst CGI nucleates on MgS.

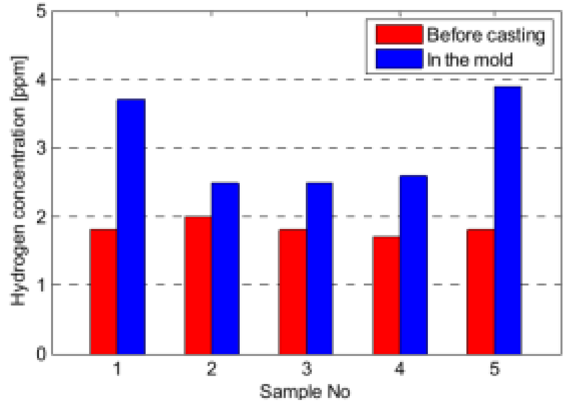

Figure 1. The level of dissolved hydrogen increases during the mould filling [Siafakas 2012].

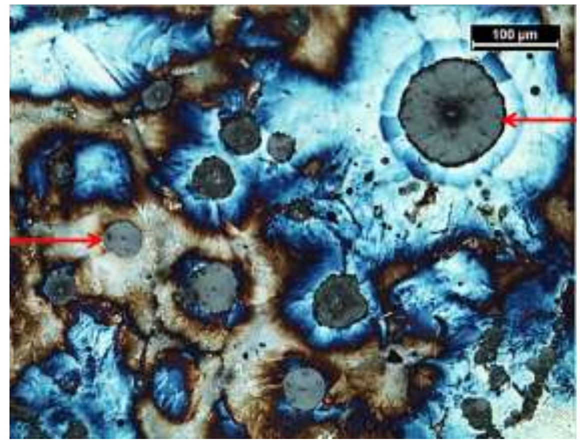

Figure 2. Grafite nodules appear in two populations [Vazehrad, project presentation 2013].

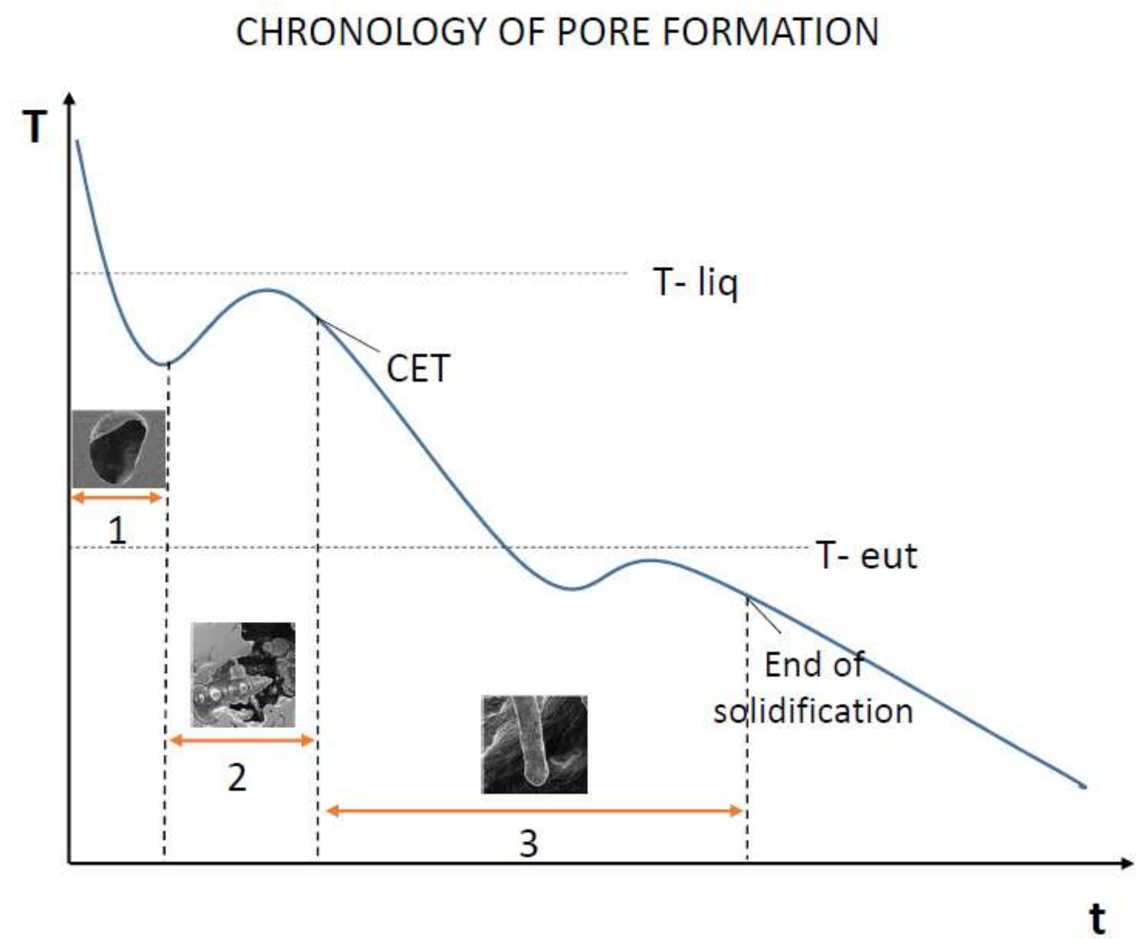

Figure 3. Different types of macro pores in CGI are formed at different stages of the solidification and cooling process.

Future research:
The project SPOFIC II is running since January 1 2014. This continuation project deepens the work regarding shrinkage porosities as well as structure formation in compacted graphite iron. Even more detailed knowledge about the solidification process and the connections between shrinkage porosities and eutectic cells as well as double populations of nodules.

Furthermore, the melting process is to be improved and the mould filling and the solidification and cooling will be simulated.

8. Participating parties and contact person

There has been five participants in the project. One university: KTH, one institute: Swerea Swecast, one sub supplier: Nya Arvika Gjuteri AB and two heavy duty vehicle manufacturers: Scania CV AB plus Volvo Powertrain AB. The key competence Attila Diószegi came to spend most of his time at Tekniska högskolan i Jönköping AB why parts of the work was outsourced from KTH to JTH.

Part	Role	Contact
Scania CV AB	Project leader, automotive industry	Jessica Elfsberg jessica.elfsberg@scania.com
Volvo Powertrain AB	Automotive industry	Kenneth Åsvik kenneth.asvik@volvo.com
Nya Arvika Gjuteri AB	Sub supplier to the automotive industry	Lars Åberg lars.aberg@arvikagjuteri.se
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