FORDONSSTRATEGISK
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Final report: Optimised Materials for Robust Machining Phase Two -
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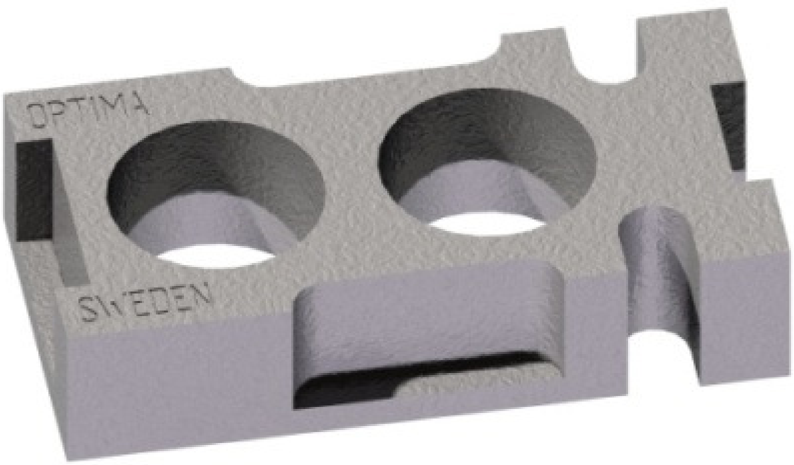

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Programme: Sustainable Production

FFI

Fordonsstrategisk
Forskning och Innovation

Contents

1. Summary

The aim of **OPTIMA PHASE TWO** has been to strengthen the basis for robust machining through new knowledge regarding the interplay between the metal cutting – the work material – the product realisation process. The correlation between work material characteristics and the machining process has been addressed in particular for compacted graphite iron (CGI), high strength alloys and combined materials. Increased productivity can be gained through improved control of material specifications, optimised machining and tooling concepts for CGI machining as well as improved understanding about the material behaviour and process modelling for combined metals machining and in-depth assessment of basic conditions for the interaction between work material and cutting tool. The project has also included initial efforts towards a production-adapted short-time machinability test and knowledge dissemination via internal seminars at participating companies and the implementation of results in educational material. The project deliverables thereby include:

- A knowledge platform for machining of advanced materials
- Optimised casting and machining of CGI
- Increased potential productivity in manufacturing chains
- Educational material for knowledge dissemination

This has been achieved through practical tests in industrial environment, model laboratory experiments, analyses and modeling/simulation of basic correlations in metal cutting with support from PhD students and scientist at in the participating universities and institute. The project has generated 3 PhDs employed in automotive and mechanical engineering industry, international co-operation and around 20 scientific publications. Since OPTIMA PHASE TWO has covered a broad range of work materials – from cast irons to high strength alloys, significant interest has been taken in generic aspects of the interaction between work material and cutting tool, even if focus has been on the casting and machining of compacted graphite iron (CGI). It is also expected that the project has contributed to the continued strengthening of a strategic network and technology platform for advanced manufacturing technology.

2. Background

Metal cutting is a core value-adding technology of the component manufacture of Swedish automotive industry. With increasing demands on improved vehicles follows requirements for increased light-weight design, lower emissions and more efficient engines and drive lines. This means that product development involving intrudction of new products and materials. Hence, research and innovation in metal cutting is of core importance for Swedish automotive industry.

3. Aim

OPTIMA PHASE TWO has therefore addressed fundamental issues of importance for realizing robust manufacture of engine components through new knowledge about the interplay between metal cutting – material and material realization process (focus on casting). By means of the knowledge gained, the project has addressed the development and optimization of future machining:

- Compacted graphite iron (CGI) - application
- High strength alloys – generic part
- Combined materials - application

4. Organisation and Activities

Strategy

The project has been based on previous results and experiences in the prior project Optima within the MERA-program. The expected outcome of the project includes as stated above:

- A knowledge platform for machining of advanced materials
- Optimized casting and machining of CGI
- Increased potential productivity in manufacturing chains
- Educational material for knowledge dissemination

This has been accomplished through knowledge development in two ways:

- Practical tests in production environment,
- Modell laboratory experiments, their analysis and process modeling/simulation including the involvement of PhD students and scientists at university and institute.

OPTIMA PHASE TWO has addressed a broad range of work materials: from cast irons to high strength alloys. Significant efforts have been therefore been placed on the generic aspects of tool-work material interaction, although there has been a focus on casting and machining of compacted graphite iron (CGI).

Organisation och Activities

Chalmers University of Technology has been overall responsible for the project with the project leader Professor Lars Nyborg, MCR c/o Department of Materials and Manufacturing Technology. Industrial co-ordinator has been Adjunct professor Göran Sjöberg, Volvo. The project has been organized in the three technical work packages:
High strength alloys – generic part (WP1)
Compacted graphite iron (WP2)
Combined materials (WP3)

The WP leaders have been:
WP1: Göran Sjöberg, AB Volvo
WP2: Hans-Börje Oskarson, MCR-Chalmers
WP3: Lars Nyborg, MCR-Chalmers

For each WP, there has been a project group with the participants involved from industry, university and institute. In addition, there has been an overall steering group. The project has involved several PhD students as follows:

WP1: Stefan Cedergren, Chalmers/Volvo/Volvo Aero
WP2: Anders Berglund, KTH, Varun Nayyar (60%), Chalmers, Mathias König, JTH (Jönköping University)
WP3: Amir Malakizadeh (f r o m Nov 2010), (50%), Chalmers

The project partners and their participation in the different WPs are shown in Table 1 below.

Partner	WP1	WP2	WP3
Volvo	X	X	
Volvo Cars			X
Sandvik Coromant/ Sandvik Tooling		X	X
Sintercast		X	
Novacast		X	
Daros/Federal Mogul		X	
Chalmers MCR	X	X	X
KTH DMMS		X	
JTH		X	
Swerea SWECAST		X	
Swerea KIMAB		X	

Initially, a smaller effort by Lund University was also planned. However, this effort has instead been solved by Chalmers based on mutual agreement.

The activities within the WPs have basically followed the original plans. WP1 has had a broader approach from materials point view than WP2, addressing the machinability of both high strength alloys, powertrain materials (steel) and titanium as well. The work within WP1 has primarily been performed by Chalmers and Volvo. Besides the PhD candidate work (Cedergren), several diploma thesis studies have also been added. In addition, international co-operation has been developed in the area of rapid deformations (UC San Diego, prof. K. Vecchio).

For WP2, focus has been placed on one kind of work material - compacted graphite iron (CGI). CGI is a candidate for replacing current gray irons in diesel engines for heavy vehicles (trucks, etc). The aims have been to understand and optimize the machining of CGI in real components, to establish a material model for casting and initial material data for future simulation of the metal cutting process. Important means for this has been the component-like test part developed in the previous project and the unique test materials including 18 variants of CGI in the form of flat (for milling) and cylindrical specimens (for turning). Within WP2, Chalmers and KTH have done the machinability research, while JTH (Jönköping University) and Swerea SWECAST have been responsible for the casting research. Swerea KIMAB has contributed with a minor effort regarding investigation of worn cutting tools used in CGI milling experiments at KTH. Sandvik has contributed with their competence to machinability studies and tooling concepts. Volvo and Scania CV have contributed extensively to the dedicated work material manufacturing and with own production development work. Sintercast and Novacast have contributed with their competence and efforts when planning and realizing the CGI test parts. The research work has then mainly been performed by the PhD students at Chalmers (Varun Nayyar), KTH (Anders Berglund) and JTH (Mattias König) and one researcher (Henrik Svensson) at Swerea SWECAST. Also, several diploma theses have been realized in support for the activities.

The WP3 on combined materials was started as a pre-study including a dedicated diploma thesis. From November 2010 a new PhD student (A. Malakizadi) was engaged on halftime within the project, with the other half of his work supported by strategic funding in Production Area of Advance at Chalmers. Volvo Cars has supported with test materials and production follow studies and Sandvik Tooling (now Sandvik Machining Solutions) has contributed with supervision and expertise (Adj. professor Ibrahim Sadik).

<u>Financing and efforts of partners</u>

The project has run during the period 2009-07-01 till 2012-03-31 with a total turnover of 17,07 Mkr, whereof 7,7 Mkr funding from VINNOVA, 9,18 Mkr industry contribution (in-kind) and 0.19 Mkr own funding from university/institute. The industrial contribution has thus amounted to more than 50% of the total costs for the project.

Co-operation and synergies with other projects
One important connection has been with the FFI-project ”Realistic Verification”, where the basics are developed for the microstructure-oriented FE-modeling of the cutting in compact graphite iron. Furthermore, through the internationalization project VERA (PTC-MCR-CAPE joint effort supported by VINNOVA), short international stays have been realized for the PhD students and researchers within OPTIMA PHASE TWO. For example, the PhD student V. Nayyar has developed co-operation with University of Tours and Safety, co-operation partners of Sandvik Coromant/Sandvik Tooling in the area of CGI machining. When it concerns the generic part (WP1), there has been a connection to materials and process modelling and development of material data, including as well studies of rapid deformation of metals (NFFP-project), including international co-operation with University of San Diego (Professor K. Vecchio). Materials and process modelling is also an active field within the excellence profile ”Sustainable Manufacturing Processes” within the Production Area of Advance at Chalmers and Lund University. For KTH, there is similar connection to their strategic initiative in production XPRES.
For casting, there are correlations to the Casting Innovation Centre (CIC) run jointly by JTH and Swerea SWECAST.

5. Results

5.1 Contribution to programme goals

Optima phase two has gathered a critical mass of collaborating industry, university and institute partners. The project has had an international connection (see above), generated PhDs and licentiates according to plans and also resulted in measurable international publication in scientific journals and conference proceedings. The results have been produced in close co-operation between the partners within the WPs and also been disseminated within the participating companies through result seminars. In addition, there is new educational material that can be used in e.g. professional education and competence development of engineers, etc.

A particular aspect of the project has been the combination of basic research concerning the components manufacture with new and/or advanced materials and the industrial competence development, jointly aimed at further fostering competitive components manufacture in accordance with overall program goals. Sweden has a world leading position in development and manufacture of engine and driveline components. The project has been centered on issues related to the casting and machining of new more strong cast irons as CGI for future engine components. The problem is the lesser machinability and more complicated casting process for CGI. The results of the project are expected to contribute to improved knowledge in support of efficient product and production development in the area of concern. The generic part on tool-material interaction in machining of advanced alloys and the start-up of the future area machining of combined materials have also been instrumental for the knowledge development and as such seen as preparatory efforts for new efforts/project where industrial need can be met.

Characteristic for the project has been the broad industrial co-operation of participating automotive industrial enterprises (Volvo incl. Volvo Aero, Scania CV, Volvo Cars) and the co-operative effort of three R&D constellations (Chalmers MCR, KTH DMMS and CIC (JTH and Swerea SWECAST). These three environments have through the project developed a joint research and innovation capacity with complementary competences and expertise. The project has also involved Sandvik Coromant/Sandvik Tooling in the metal cutting research as well as Sintercast, Novacast and Daros (Federal Mogul) contributing with unique expertise regarding casting f compacted graphite iron.

5.2. Summary of important results

WP1: High strength alloys – generic part

This WP has addressed the machinability critera for high strength alloys. A broadened approach including the machining of carbon steel, stainless steel, nickel alloys and titanium (Ti-6-4) has been applied. The basic idea has been to better understand the role of the microstructure of the work material for the phenomena/local processes that take place in metal cutting. One important observation is that the grain size has an important role for chip formation process and burr formation. The model is that the amount of material being cut in comparison to the material microstructure (grain size) is of prime importance (see Figure 1).

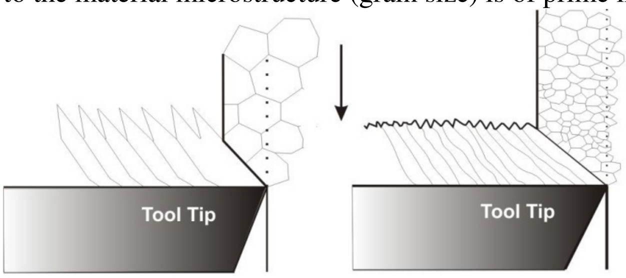

Figure 1. Basic model for effect of microstructure (grain size) on chip characteristics in metal cutting of high strength alloys.

The phenomenon illustrated in Figure1 has been addressed further by means parametric machining studies. A clear transfer from continuous chips to segmented ones was observed for small grain sizes, while this transformation was more unclear because of the anisotropic deformation for coarse grained material. Model and theory development for these phenomena have been developed considering aspects of e.g. adiabatic conditions. The occurrence of specific wear mechanisms as for example notch wear and burr formation have been further investigated in WP1. Burr formation has been observed for stainless steel as well as for alloy 718 connected to feed values and grain size effects for the materials. In machining case hardening steel in normalized condition, consisting of soft ferrite and relatively hard pearlite, the effect of feed on burr was different. To complete the picture of work material influence, machining of Ti (Ti-6Al-4V) in three different conditions (Figure 2) was studied.

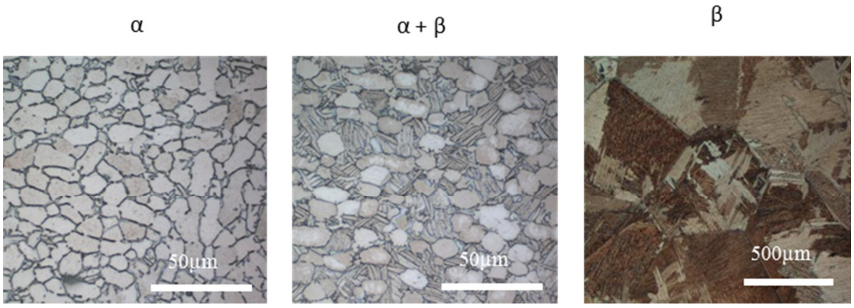

Figure 2. Microstructures of Ti-6Al-4V used in machining studies.

Despite certain deviation in hardness, no significant differences in cutting forces were found when machining the different titanium conditions. The inhomogeneous deformation for the β-condition gave higher acustic emission independent of feed. For the two other conditions, α and α + β, increasing periodic segmentation with increasing feed correlated well with increased acoustic emission (Figure 3).

When establishing criteria for burr formation, grain size is not enough to consider, also crystal structure and different combinations of such must be included in models. When grain size has been identified as crucial factor for the tool wear, the mechanical properties are neither enough for assessing the effect.

Knowledge about role microstructure and cutting parameters in combination is crucial for assessment of machinability of different materials and can be used as basis for adaption of cutting data in production.

Understanding the role of microstructure for burr formation provides a way of tailoring material specifications to counteract burr and to reduce costs for unwanted extra operations.

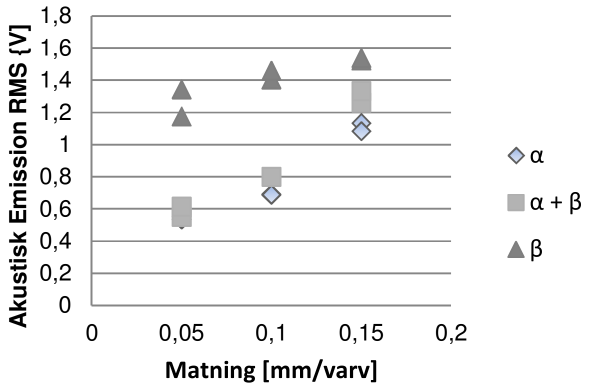

Figure 3. Correlation between acoustic emission (RMS) and feed when machining titanium (Ti-6-4) in different conditions.

WP2: Compacted graphite iron (CGI)

The aim of this WP has been to develop a knowledge platform for casting and machining of advanced cast irons in support for future manufacture of engine components. The overall goal has been to find out how robust machining can be achieved without compromising with design rules for microstructure of compacted graphite iron.

In component manufacture, critical machining operations are crucial for the overall efficiency. The work has therefore been focused on milling and boring studies including tests in a component-alike test part (Figure 4) to:

- Investigate how tooling concepts and cutting data can be used to tailor and optimize the milling and boring in CGI
- Build a model for optimized milling/boring in CGI. The model is supposed to account for work material microstructure, insert characteristics and cutting data.

Different test geometries, such as plates, cylinders, component-alike test parts and a special cylinder for "simulated milling" have been cast in great number. The goal has been to find out how potential differences in e.g. microstructure from component to component could vary, but also establish how microstructure variation within a part could be. Table 2 shows results from mechanical testing for specimens taken from three out of five cylinder parts. For the machining studies, it is then of great importance that homogenous properties are obtained for the test parts machined. Extensive materials characterization and testing showed that this was the case.

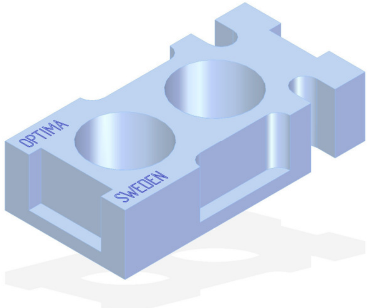

Figure 5. Component-alike test part for experimental simulation of machinability of relevance for real parts.

Table 2. Results from mechanical testing of samples taken from three different cylinder parts of same CGI variant

Prov	Rp0,2 [MPa]	Rm [MPa]	A5 [%]
C1	298	403	1,7
C2	300	404	1,8
C3	317	422	1,7

When considering continuous machining operations (like boring) studies show that tool wear of hardmetal inserts is strongly correlated to the CGI characteristics as tensile strength, hardness and pearlite content. Cutting forces, however, do only show minor increase with increasing work material (CGI) tensile strength. The tensile strength depends on the nodularity, pearlite size, and pearlite content in the material. For continuous machining operation, the tool life and cutting forces have therefore been correlated with pearlite content and nodularity. The results are summarized in an empirical model shown in Figure 5. The model is valid for nodularity of between 3-32% and pearlite content of between 21-98%.

In order to further understand the conditions prevailing in the cutting zone, the effect of cast iron structure and cutting parameters on tool temperature was investigated. This was done by recording the temperature in the tool at the clearance face. From the experiments, it was found that this temperature was correlated to the cutting speed, but not to the tensile strength of the CGI material.

In general, the studies performed have shown that lower cutting speed and higher feed are recommended for best productivity when machining CGI in continuous operations. Studies of chips have shown that the chip characteristics are suitable for all variants independent of cutting speed. The role of cutting fluid is crucial, since use of cutting fluid means lower cutting forces for all CGI variants. In addition, the cutting tool characteristics (e.g. egg radius) are important. A special study was here performed with different egg radii for two different cutting tool geometries, where the effect of these parameters on tool wear and machined surface topography were depicted. In similar way, the role of edge geometry of spiral drills was investigated.

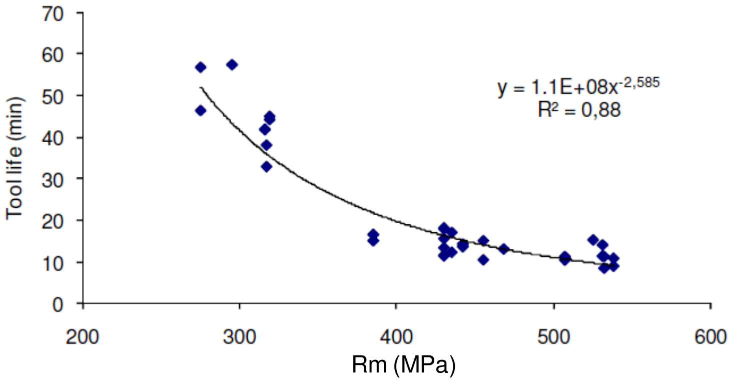

Figure 5. Correlation between tool life and tensile strength of CGI variants machined.

In the case of intermittent machining (like milling) of CGI, the fact that the pearlite content has decisive effect on the tool life was confirmed, see Figure 6. It was confirmed that variation in nodularity in the interval below 20% did have any impact on the machinability, while presence of hard primary carbides (governed by the content of carbide formers as chromium) has significant impact on the tool life. Finally, there overall effect of cutting parameters (speed and fee) was investigated and the role of increased cutting speed with associated abrasive tool wear in determining tool life could be verified, while the correlation between different cutting data and change sin tool wear were clearly observed. To facilitate improved understanding regarding the fundamental aspects in intermittent cutting processes on CGI, an initial thermo-mechanical FE-model was developed with support from in-situ temperature measurement using heat camera and so-called quick stop tests. Figure 7 illustrates a temperature distribution according to the FE-model.

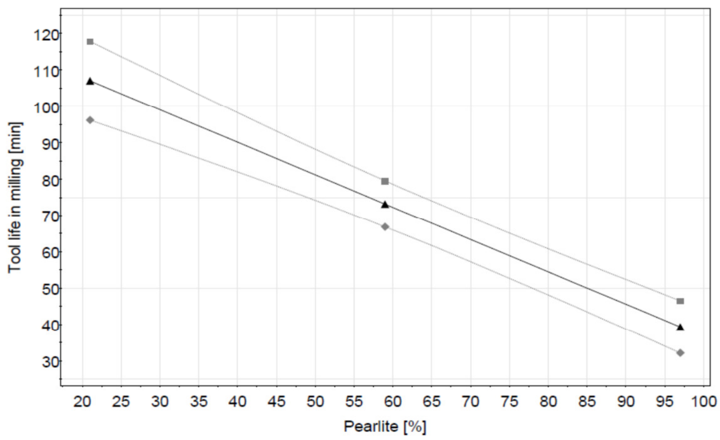

Figure 6. Effect of CGI microstructure (pearlite content) on tool life in milling.

The development of different CGI structures depend on the material composition and casting. The possible variation in structure within a component as well as that between batches can be an issue for the machining operations in production. An initial study to find out possible short-term machinability tests was therefore also accomplished and special boring test was developed for further work.

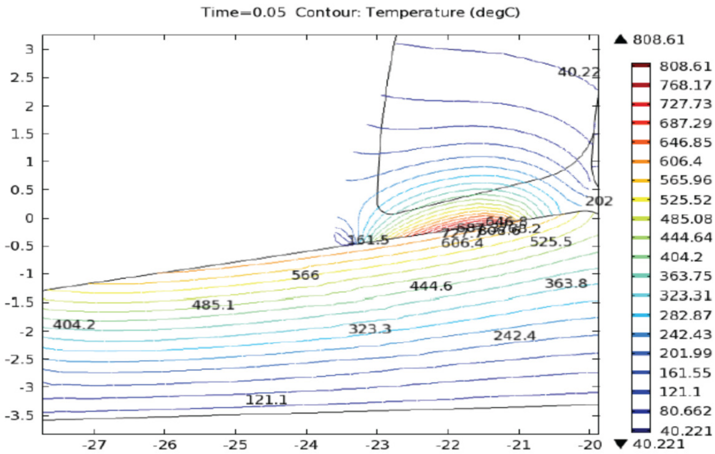

Figure 7. Illustration of temperature distribution obtained by means of thermo-mechanical FE-model. The experimental data points in the figure are for 0.05 s after the engagement.

When it concerns material and modelling (with reference to the casting) three major issues have been i) the microstructure development during the solidification of CGI compared to that of other graphitic cast irons, ii) the microstructure development at lower temperatures at the transformation of austenite to ferrite/pearlite and iii) the effect of alloying elements and CGI microstructure on mechanical properties (and thus on machinability as evidenced above). Cast irons as CGI usually experience grey solidification and the results illustrate the potential variation in structure development depending on solidification rate and role of factors as inoculation, melt treatment and section thickness. So called white solidification (primary cementite formation) is important to avoid since this will deteriorate the CGI properties. This phenomenon was studied using wedge tests and it was confirmed that the risk for white solidification is similar for CGI and nodular iron, while grey is less sensitive. For the solid state transformation from austenite to ferrite/pearlite in CGI, a model has been developed from models for nodular iron. The role of alloying elements and cooling rate were investigated by means of thermal analysis as well as sand cast test specimens for a great number of different CGI variants and cooling rates. A common conclusion is that the alloying elements to significant degree will affect both the ferrite and pearlite formation and thus also the mechanical properties, see Figure 8.

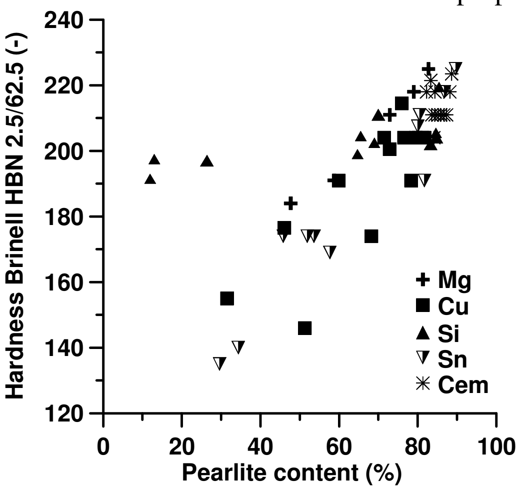

Figure 8. Hardness for the 57 different variants of test specimens fabricated with different cooling rates, alloying content and pearlite content.

WP3: Combined materials

The work in this WP has been orientated at experimental machining studies using model combined material work-piece in laboratory, industrial production development studies and the development of methodology for determining material data (material model) for FE-modelling of machining by means of orthogonal turning experiments and inverse modelling approach. Figure 9 illustrates an experiment where machining of cast aluminium has been compared with machining of a combined material (test piece comprised of the cast aluminium and CGI). As can be seen from Figure 10, there is quite different response in cutting forces for the two situations. In parallel with the laboratory studies, Volvo Cars has addressed the machining (milling) of engine blocks made of aluminium with grey iron cylinder liners as a basis for further R&D activities.

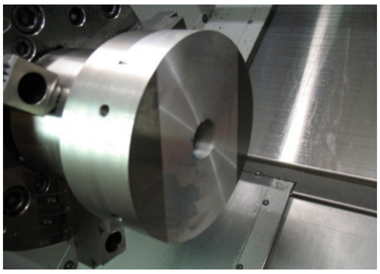

Figure 9. Work piece: combinedimetals, face turning.

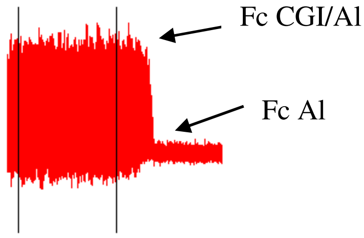

Figure 10. Cutting force variations: combined metals machining..

Figure 11 presents the concept developed for determining material models for FE-simulation of the metal cutting process. The methodology has been successfully applied for the machining of high strength alloys (Alloy 718), an aluminium alloy and a steel, where relevant material data (material models) have been derived and then used in 3D simulation of the metal cutting process using commercial software. The results show that the FE-calculations can be used for simulation of the metal cutting process provided there is a functioning material model. The application can even be to study the machining of combined materials and optimize cutting data and cutting tool characteristics without extensive experiments.

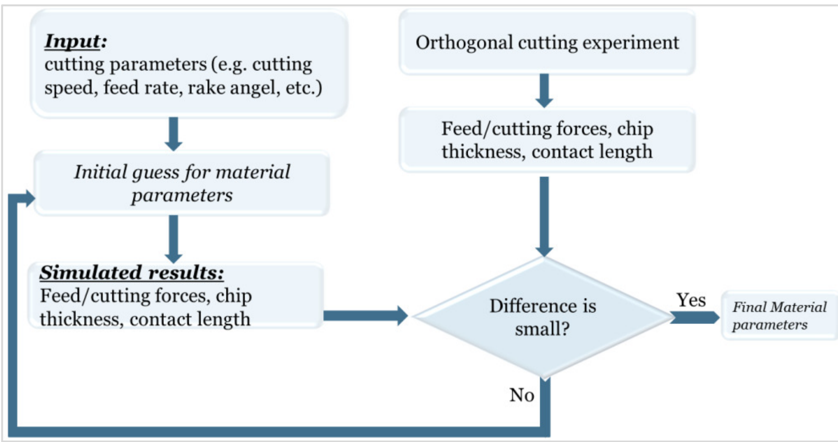

Figure 11. Inverse modelling concept for development of material model for Fe-simulation of metal cutting.

6. Knowledge dissemination and publication

6.1 Knowledge and results dissemination

Two PhD students (Anders Berglund and Mathias König) have accomplished their PhD degree within the project are now employed at Scania CV. One further PhD exam is scheduled (Varun Nayyar, 1 juni 2012) and Varun Nayyar is also from 2012 employed at SKF. The PhD students Amir Malakizadi and Stefan Cedergren will present their licentiate theses during spring 2012 and are expected to continue their PhD studies within a new project. The results gained within the project have been disseminated to Swedish industry via program conferences and in particular the yearly running national cluster conference in Katrineholm. Results have also been presented at the yearly running Swedish Production Symposium (see publication list below). To enhance the knowledge dissemination within the organisation of the participating partners, there have been two results seminars in Skövde and Södertälje. A special effort has also been the development of educational material for knowledge dissemination regarding casting and machining of compacted graphite iron. Besides the scientific publication (see below), a number of diploma thesis studies (10) have also been performed connected to the project.

6.2 Publications

PhD theses

- Mathias König, Microstructure Formation During Solidification and Solid State Transformation in Compacted Graphite Iron. JTH/Chalmers, 2011.
- Anders Berglund, Criteria for Machinability Evaluation of Compacted Graphite Iron Materials: Design and Production Planning Perspective on Cylinder Block Manufacturing. KTH, Skolan för industriell teknik och management (ITM), Industriell produktion, 2011.
- Varun Nayyar, Machinability testing of Materials in Metal Cutting with Focus on Compacted Graphite Iron and Cutting Fluids. Chalmers (disputation juni 2012)

Licentiate theses

- Anders Berglund, Characterization of factors interacting in CGI machining – machinability, material microstructure, material physical properties, KTH, Industriell production, 2008.
- Gustav Grenmyr, Investigation on the Influence of Nodularity in Machining of Compacted Graphite Iron (CGI), Chalmers, 2008.
- Mathias König, Microstructure Formation and Mechanical Properties in Compacted Graphite Iron, JTH/Chalmers, 2009.

International publication

- S. Cedergren et al., On the Influence of Work Material Microstructure on Chip Formation, Cutting Forces and Acoustic Emission when Machining Ti-6Al-4V, submitted to the 8th CIRP Conference on Intelligent Computation in Manufacturing Engineering
- S. Cedergren et al.The Effects of Grain Size and Feed Rate on Notch Wear and Burr Formation in Wrought Alloy 718, submitted to the International Journal of Advanced Manufacturing Technology
- V. Nayyar et al., An experimental investigation of temperature and machinability in turning of compacted graphite irons. Accepted for Int. J. Machining and Machinability of Materials, 2011.
- V. Nayyar et al., Machinability of Compacted Graphite Iron (CGI) and Flake Graphite Iron (FGI) with coated carbide. Accepted for Int. J. Machining and Machinability of Materials, 2011.
- V. Nayyar et al., Temperature in Turning of Compacted Graphite Iron Materials having different Physical properties and Microstructure. Swedish Production Symposium 2011.

- V. Nayyar et al., Machinability of Compacted Graphite Iron (CGI), a Microstructural and Mechanical Properties Comparison Approach. Swedish Production Symposium 2009.
- A. Berglund et al., Effect of carbide promoting elements on CGI material processing. CIRP 2nd International Conference on Process Machine Interactions, Vancouver, 2010.
- A. Berglund et al., The Effect of Interlamellar Distance in Pearlite on CGI Machining. Proc. World Academy of Science, Engineering and Technology, ISSN 2070-3740; 4. 2009.
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- A. Berglund et al.,Investigation of the Effect of Microstructures on CGI Machining Swedish Production Symposium, 2007.
- G. Grenmyr et al., Investigation of tool wear mechanisms in CGI machining. International Journal of Mechatronics and Manufacturing Systems, ISSN 1753-1039. 2011.
- M. König et al.,(2011), On Eutectic Growth in Compacted Graphite Iron, submitted to Metallurgical and Materials Transactions A.
- M. König et al., The Influence of alloying elements on Chill Formation in CGI, Proceedings of Science and Processing of Cast Iron – 9, November 9-13, 2010, Luxor, Egypt, pp. 126-31.
- M. König et al., (2011): "Observation and Simulation of White Solidification in Compacted Graphite Iron", submitted to International Journal of Cast Metals Research.
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- M. König et al., Influence of Alloying Elements on Microstructure and Mechanical Properties of CGI, International Journal of Cast Metals Research, 2010, 23, no. 2, pp. 97-110.
- M. König et al., The Influence of Copper on Microstructure and Mechanical Properties of CGI", International Journal of Cast Metals Research, 2010, 22, No. 1-4, pp. 164-67.
- M. König et al., "Literature Review of Microstructure Formation in Compacted Graphite Iron", International Journal of Cast Metals Research, 2009, 23, No. 3, pp. 185-92.
- A. Malakizadi et al., "An Inverse Algorithm to Determine Material Flow Stress in Metal Cutting Process Using Oxley's Machining Theory and Surface Response Methodology", in manuscript.

7. Conclusions and Future Research

OPTIMA PHASE TWO has led to a joint technology and knowledge platform involving the partnership of automotive industry, other industry, university and institute. Through this generic knowledge development and innovative solutions for future components manufacture can be realized. Broad knowledge regarding the machinability of different materials as well as more focused understanding with reference to in particular compacted graphite iron and high strength alloys. Important issues for future research will be take advantage of the knowledge and methods developed to bring appropriate methodologies and working concepts for production-adapted and needs-oriented assessment of machinability, to initiate efforts in which machinability aspects and system perspectives are combined and finally to further govern the initiated competence development regarding combined materials machining and the methodology set up for development of practical models to be used in metal cutting simulations.

8. Participants and contact persons

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Kurt Forsberg
Sandvik Tooling: Ibrahim Sadik
Novacast: Per-Eric Persson

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JTH: Ingvar Svensson
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