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Realistic verification of manufacturing processes - step 1

Project within sustainable production

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Content

FFI in short

1. Executive summary

It is a key issue for the automotive manufacturing industry to sense, and to have the ability to act on changes on the market with respect to environmentally friendly and lightweight products. Special concerns relate to enhanced product performance and the need to reduce fuel consumption; the latter need is directly linked to reduced emissions and smarter environmental impact. A key enabling technology to accomplish this is to exploit advanced materials, processing and machining via virtual simulation technology. Indeed, there is a need to enhance the manufacturing via capable, cost-efficient, and robust simulation tools for specific operations of the production processing chains.

In the project we address a couple of key issues related to realistic verification of manufacturing processes based on virtual simulation tools. The issues involve material modelling, material science, experimental and system oriented perspectives of manufacturing processes. On the one hand, the issues relate to simulation of the *machinability of heterogeneous cast iron materials* and, on the other hand, issues relate to a system oriented formulation of the *heat assisted processes of press quenching*, used to control distortion of case hardened crown wheels. We thus focused a few steps towards the ultimate goal of providing virtual tools where all manufacturing processes can be tested virtually in a realistic manner.

As to heat assisted forming processes, we develop a methodology to analyze how various properties and parameters influence the distortion during press quenching of crown wheels. Distortion in crown wheels may cause excessive grinding, assembly problems, unfavorable load distribution, continuous noise of parts in service and even scrapping. The unsystematic distortion is due to non-uniformity in the steel properties and processing conditions and is a major concern for gear manufactures. To obtain realistic quenching characteristics, to be used for process simulation, a number of experiments are carried out on an industrial press quenching machine. Based on the experimentally obtained quenching characteristics the press quenching process is simulated by FEM.
A prediction tool for how the press quenching operation affect important geometrical features for a crown wheel has been developed. The tool is based on 24 FEM-simulations where the steel hardenability and press forces were varied according to DoE-plan. From the simulations data was extracted and used for creating linear regression models for the prediction of crown wheel geometry after press quenching. The regression models was then tuned with data extracted from physical DoE-experiments performed at Scania.

To characterize machinability of heterogeneous cast iron materials, we identified an innovation agenda, comprising the current state of the art machining simulation methodology along with research issues of numerical simulation and experimental. The following main components define the agenda:

- virtual simulation strategy for 2D cast iron machining
- machining experimental associated with virtual simulation of orthogonal cutting

- model parameter identification strategy
- prototype tool for making predictions of machinability of the work piece material

To arrive at a predictive method (and tool) the microstructure for range of cast iron has been considered in the agenda. Please note that the microstructure can be varied with respect to cast iron nodularity using virtual testing, whereby the complete range from “gray iron” to CGI and nodular cast iron" are handled. The crucial material modeling development in the agenda has been made related to: “consistent heat generation”, “modeling ductile fracture and damage” related to chip formation. Different model assumptions have been developed due to computational robustness, on the one hand, and, on the other, hand predictive model capability. A 2D test describing a 2D machining situation, named the “sliced cylinder” concept, was developed along with the model parameter identification strategy. Based on the prototype tool we carry out predictions of cutting forces for a class of cast iron. Please note the predicted qualitative reduction of cutting force as the cutting speed is increased. We also note the increase of cutting force with cutting depth as well as with nodularity approaching the CGI-type. The message from the predictions is that it is possible to make virtual variations in the cast iron materials and to make qualitative judgments of cast iron machinability.

2. Background

A key factor for the competitiveness of the Swedish manufacturing industry is to realize rapidly new products, and at the same time to develop the manufacturing process as efficiently as possible. It is also crucial to maintain and to further develop manufacturing methodologies to enable smart energy use through “lightweight components”. This places high demands in using advanced high-strength materials in the machining processes. The proper management of the involved process parameters is of major importance. Typically, virtual simulation of manufacturing processes are frequently used, cf. Ahlström and Larsson [1]; however, much more research is needed to further enhance this technology.

Case hardening entails the treatment of a finished part in a carburizing atmosphere at a high temperature normally 850–950°C, which increases the carbon content at the surface of the part. Parts that are case hardened receive a hard surface and a softer and tougher core. This entails a very good combination of properties: high strength, wear resistance and toughness. One of the challenges with case hardening is to handle distortion evoked by the heat treatment process. The total production cost is strongly dependent on how this distortion can be forecasted and controlled. Distortion resulting from heat treatment usually entails changes to both dimensions and form, thus requiring machining or straightening to obtain the desired shape after hardening. As to the crucial machining processes, knowledge of cutting forces, chip morphology, temperatures, surface integrity, tool life, etc., is an important prerequisite for reducing machining costs and improving product quality. Today machining processes can be described in a much more realistic manner using virtual simulation technology, and the current state of the art research involves simulations based on the microstructure of the material.

3. Objective

The objective of the project was to increase and spread the knowledge of the links between manufacturing process parameters and the final product properties, using numerical simulation and experimental methodology assist. To develop the objective, we crystallized issues of distortion and residual stresses, placed in context with machining/forming/heat treatment processes, as well as process parameters, like cutting forces as induced by the machining of heterogeneous materials, like cast iron. In this development, research on "realistic verifications" with a focus on material modelling and model identification has been identified as the key enabling technology. The crystallized issues of the manufacturing are strategic in introducing *new materials in the manufacturing processes*, which in turn is the main enabler towards powertrains with smart environmental impact. Thereby, the road map "2020 Sustainable manufacturing systems capable of producing innovative environmentally friendly and safe products" is well in line with the objectives on numerical simulation and experimental methodology assist in the manufacturing.

4. Project realization

The project was subdivided into three main work packages WPA, WPB and WPC with major focuses according to

- WPA – focusing the influence of process parameters on powertrain components, where the major milestone is to develop a tool for prediction of how the quench press shall be operated regarding pressing forces depending on the chemical composition of the steel grade used. The tool is based on a combination of process data and geometrical data from press hardened crown wheels and FEM-simulations (software Sysweld from ESI Group) were different press forces and chemical compositions of the steel are accounted for.
- WPB – focusing the modelling and simulation of machining heterogeneous materials. In this work package we crystallized an innovation agenda targeting cast iron machinability. The agenda comprises the current state of the art methodology for virtual machining simulation along with and research issues of fracture modelling, material damage along with the proper materials characterization of heterogeneous materials.
- WPC – Project management and coordination of WPA and WPB activities in project meetings. Participation in international conferences, publication in international journals, and knowledge spread in Sweden by initiation related themes, at e.g. the Katrineholmskonferensen, in order to strengthen the competitiveness of the Swedish manufacturing industry in terms of its productivity via increase of competence and awareness of virtual simulation technology.

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WPA - Influence of process parameters on crown wheel manufacturing

In order to develop the tool for prediction of distortion a combination of data from production, planned experiments in industrial and semi-industrial conditions, FEM-calculations and multi-variant methods have been used. Much effort was put in to the task “production data analysis” and establishing the heat transfer coefficients during the oil quenching in the press quenching unit. The FEM-analyses were necessary for understanding the effect of press quenching on size and changes of shape.

The work has been conducted in close cooperation between the industry, university and institutes. This is a key-factor in reaching the major milestone of this task of the project.

WPB – An innovation agenda for virtual simulation of cast iron machining

In order to arrive at and to comprehend the complex task of characterizing cast iron machinability an *innovation agenda* was defined. The agenda comprises the current state of the art machining simulation methodology along with research issues of numerical simulation and experimental technologies targeting cast iron machinability. The following main components define the agenda:

- virtual simulation strategy for 2D cast iron machining
- machining experimental associated with virtual simulation of orthogonal cutting
- model parameter identification strategy
- prototype tool for making predictions of machinability of the work piece material

In order to arrive at a predictive method (and tool) the microstructure for a range of cast iron has been considered in relation to machining. Please note that the microstructure can be varied with respect to cast iron nodularity using virtual testing, whereby the complete range from “gray iron” to CGI and nodular cast iron" are handled. The material modeling development has been made related to: “consistent heat generation”, “modeling ductile fracture and damage” related to chip formation. Different model assumptions have been developed due to computational robustness, on the one hand, and, on the other, hand predictive model capability. As to the machining experimental, an active decision was made in the consortium to confine to cast iron materials. As alluded to above, a 2D test that describes a 2D machining situation was developed named the “sliced cylinder” concept. This experiment was modeled with the simulation technology for verification/calibration against homogeneous pearlite material.

WPC – Project lead and administration

The project management involves the arrangement of agendas for the internal as well as formal project meetings, thereby keeping track of the current state of the art in the project group in relation to the project milestones. A common disk area has been arranged for the project where all the material produced and presented in the project is recorded. To arrive at a successful project results, we emphasize the importance of the proper project lead, in particular ways to interact within WPB has been developed. This interaction concerns Chalmers environment, between Applied Mechanics and Materials and Manufacturing Technology department, and between the interested and keen industrial partners of the project.

5. Results and deliverables

WPA - Influence of process parameters on crown wheel manufacturing

A much deeper knowledge about crown wheel manufacturing and its final appearance regarding size and shape has been gained based on a statistical approach for analyzing process- and product data. Important underlying process data such as the cooling ability of the press quench unit has been documented using experiments. Figure 1a shows the test part of a crown wheel. The part was made in stainless steel to avoid latent heat generation from phase transformations. The flags indicate thermo-couple positions. In Figure 1b cooling curves from one of experiments are shown. In Figure 2 the heat transfer coefficients that are acting on the top and the bottom of the crown wheel during press quenching are shown. These coefficients were calculated using inverse methods. The combination of data from production, FEM-simulations and multivariate analysis was a successful way of developing the prediction tool for crown wheel distortion. In Figure 3 and Figure 4 the effect of press quenching is compared with quenching with no applied pressing forces in the press quench unit.

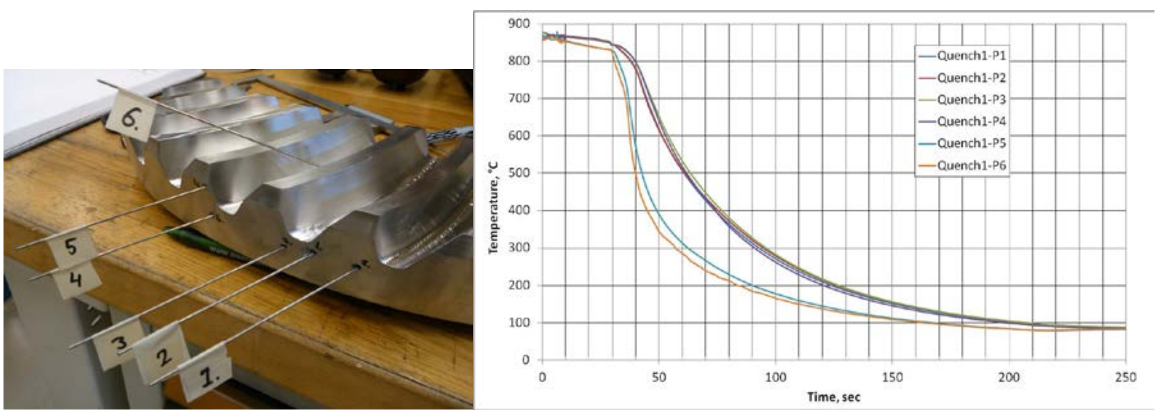


Figure 1 a) Test part for quenching experiments, b) temperature recordings from one of the quenching experiments.

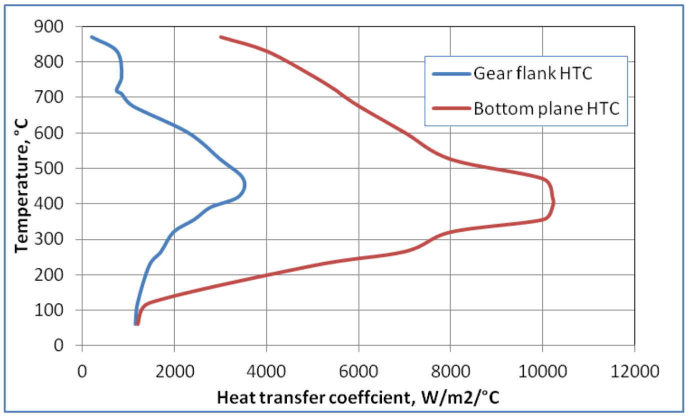


Figure 2 Resulting heat transfer coefficients used for Gear flank and Bottom plane.

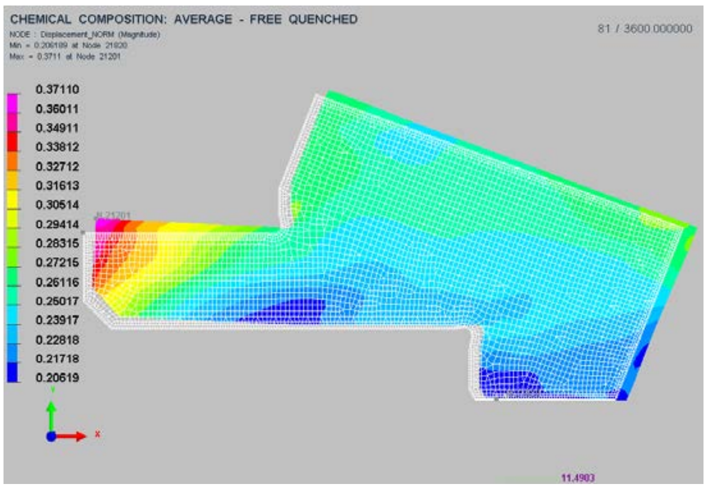


Figure 3 Normalised displacement and distortion for free quenched crown wheel with medium chemical composition. Distortion magnification 10x.

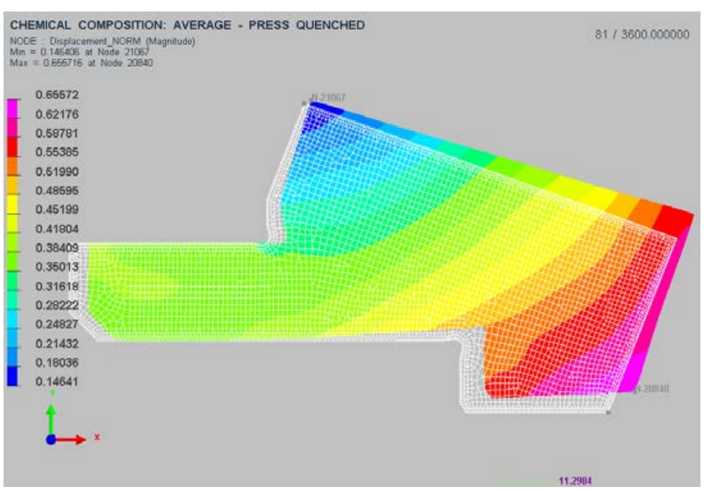


Figure 4 Normalized displacement and distortion for press quenched crown wheel, run no 8, with medium chemical composition. Distortion magnification 10x.

The developed tool is possible to adapt to forged blanks from different suppliers using a proposed method including an experiment planned according to a DoE-concept. The prediction tool is shown in Figure 5.

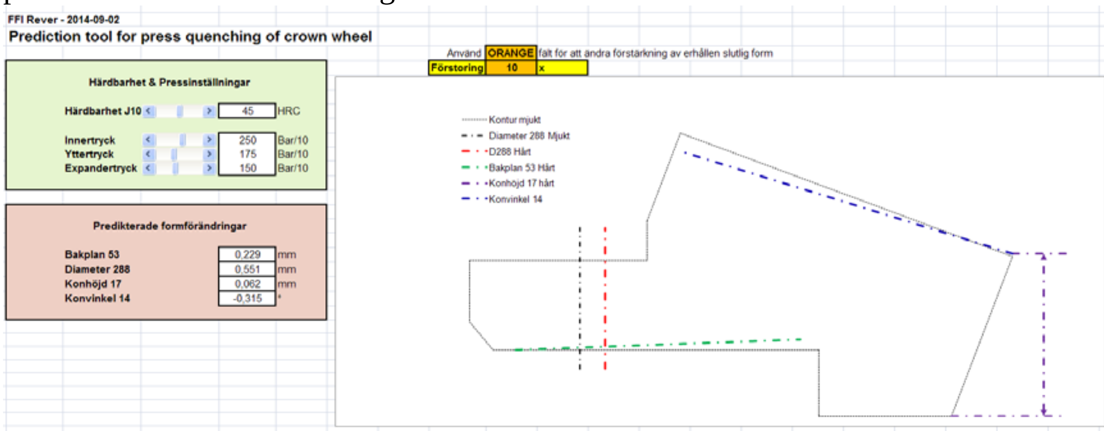


Figure 5 Screen dump from the prediction tool spread sheet.

WPB: Modelling and simulation of machining heterogeneous materials

According to the innovation agenda for characterizing cast iron machinability the main results of WPB are outlined as follows: Based on the current state of the art of numerical simulation and experimental technologies, the agenda comprises the four components: *Virtual simulation strategy for 2D cast iron machining.* In this part, we are concerned with material characterization of micro-structures in 2D via micro-graphs to identify nodularity of the cast iron material microstructure. Special technologies are developed to make images and FE-discretization, cf. the software OOF2 in ref. [2], of the cast iron microstructures. Figure 6 shows the steps of micro-graph generation, FE-discretization and analysis. As to the material modeling, we develop the concept of thermodynamically consistency with respect to rate and temperature dependence, damage and fracture modeling, cf. ref. [3]. An attractive robust and efficient model has been developed, where various ways to describe damage evolution have been investigated, cf. [4,5]. Note the close fit between the modeled chip shapes as compared the experimental, obtained in the simulation, cf. Fig. 7ab.

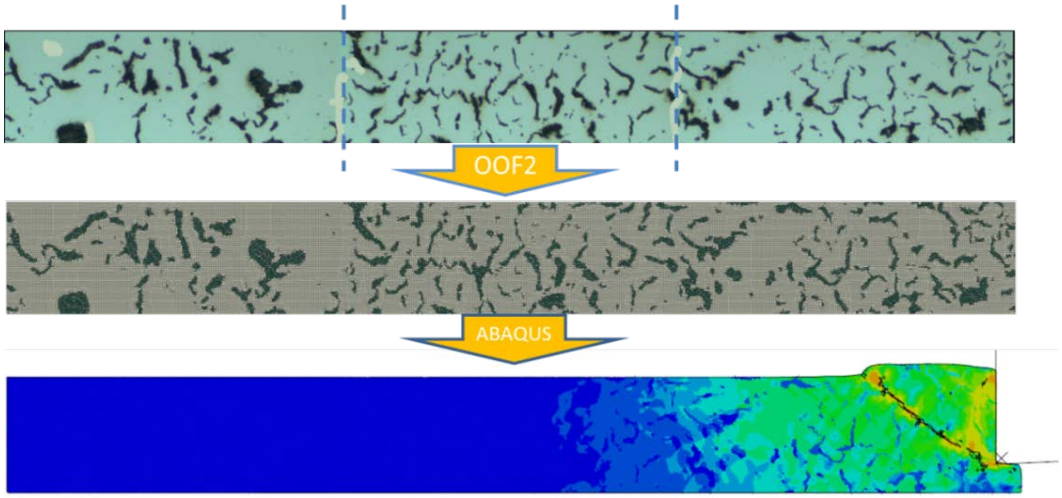


Figure 6 a) FE discretization from micro-graphs, and b) FE cutting simulation based on FE-discretized micrographs.

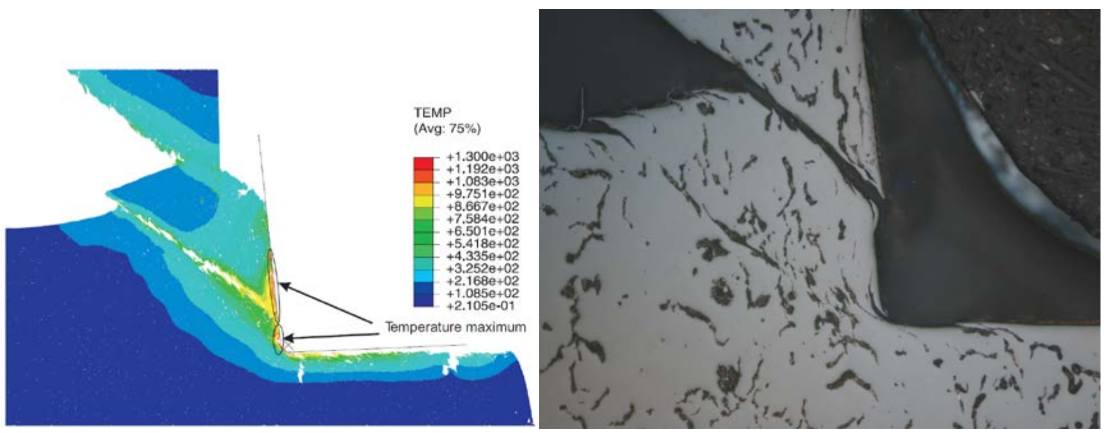


Fig. 7 a) Typical temperature distribution and chip shapes from machining simulations. b) Observed chip shapes from a "quick stop" test.

Machining experimental associated with virtual simulation of orthogonal cutting. This is crucial part of the agenda, concerned with the proper machining set–up for orthogonal cutting. To enable the synthesis between material modeling and characterization linked to robust computations, a 2D machining case associated with the 2D simulation strategy is defined for model validation and further assessment of machinability of work piece material. A "sliced cylinder concept" is thereby proposed, see Fig 8, where focus is placed on cutting force measurements and maintaining the proper cutting speed conditions, cf. Fig. 9a. A crucial part of the "sliced cylinder concept" is to ensure that the cutting force measurements are designed with due consideration to the 2D simulation strategy.

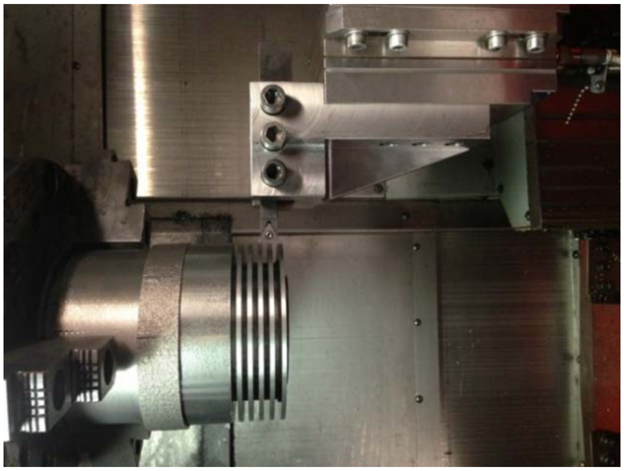
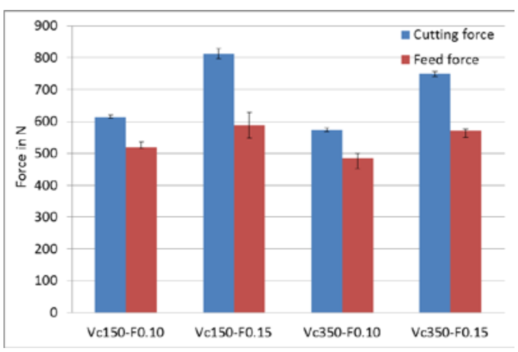


Fig 8. Sliced Cylinder test set-up with cutting conditions relating to cutting speed, feed rate and depth of cut (=constant).

Model parameter identification strategy. In this part of the agenda we are concerned with the strategy for identifying the model parameters. To this end, we resort to an inverse FE–based modeling method, based on actual the machining experimental to calibrate the model parameters, as described in ref. [6]. The basic ingredients of the method involve experimental on pure pearlite for parameter calibration and validation on a class of cast iron materials. In this development we fit the observed responses of cutting forces and chip formations with the involved material parameters based on FE-analyses for parameter identification.



	CGI (C5)			
feed (mm)/speed (m/min)	*D 100*	*D 110*	*D 120*	*Mean*
0.1/150	290	284	282	285
0.1/350	295	278	282	285
0.15/150	337	351	393	360
0.15/350	321	379	365	355

Fig. 9. a) Measured feed and cutting force of CGI (C5 one of the test specimens) material for test specimens. b) Obtained cutting forces from virtual simulation for different feeds and cutting speeds.

Prototype tool for making predictions of machinability of the work piece material. Based on the prototype tool we carry out predictions of cutting forces for a range of cast iron. We carried out parametric studies with respect of nodularity variations or other types of parameter variations. Results from this part of the agenda are shown in Fig. 9b, where inverse analysis step was made to obtain the material parameters prior to the prediction and validation step. Please note the obtained qualitative reduction of cutting force as the cutting speed is increased. Note also the qualitative increase in cutting force with the cutting depth. The important message from the predictions is that it is possible to make virtual variations in the cast iron materials and to make qualitative judgments of the machinability.

Delivery to FFI-goals

Within scope of the project we have delivered virtual tools and results related to the key WPs: “influence of process parameters on crown wheel manufacturing” (WPA) and the “innovation agenda for virtual simulation of cast iron machining” (WPB). Based on the findings in these WPs, we have the ability to vary important manufacturing parameters based on virtual simulation, providing feedback to the resulting component properties, which (properly used) leads to a greater flexibility in the production process e.g. when making design changes and/or optimizations. The cases considered represent current industrially driven problems of manufacturing involving generic disciplines as mechanical modelling, material science and system orientation. In this fashion the methodologies produced within the project are firmly founded in science, thus promoting the crucial “sustainability” also in the methodology development.

From the outset, the project directly targeted the goals of the sustainable production technology program, where “virtual process simulation” is the main enabler towards capable, cost-efficient, and robust implementation for specific operations included in the processing chains. The key point is that much time and money can be saved using virtual simulation at an early stage in the planning of the manufacturing of e.g. mixed material components as compared to trial and error methodologies.

6. Dissemination and publications

Knowledge and results dissemination

Within the scope of the project we had 9 project progress meetings with representatives from all the partners of the project. From each of these meeting the SOTA has been recorded and stored on the common disk area.

The project part WPB has been part time supported from the Chalmers area of strength Production, where the project leader (Ragnar Larsson) is responsible for the active field “Process modeling and materials assessment”. Moreover, “realistic verification – step 1” is considered as a core project at Chalmers - MCR on virtual simulation technology. A wider spread of the project scope and results has thereby been facilitated, through internal workshops at Chalmers within area of strength production and also own workshop initiatives. Recently, we also initiated the special session theme named ”Bearbetning – Virtuell teknik” at “Katrineholmskonferensen” in May 2014. The project SOTA and results were then successfully presented under the title ”Innovativ virtuell teknik för gjutjärnsbearbetning”.

In addition the results of the project have been presented at international conferences, cf. refs [8-15] and journal publications, cf. refs [2-5]. Invited keynote lectures presentations have been presented at GAMM 2012 (Tyska mekanikdagarna) and at MekIT 2013 (Norska mekanikdagarna). Project part WPB has resulted in one Lic Eng exam, Amir Malakizadi, cf. ref [6], and one PhD exam, Goran Ljustina, cf. ref [7], today employed by VolvoCars engine as Senior Tooling Engineer. We also emphasize the project lead, where sound milestones are defined, carefully monitored and progressively redefined. This has been identified as an important factor to arrive at successful project drive. In particular, with respect to linking different parts, people and organizations to each other, thereby facilitating the right motivation for further knowledge spread of the project result.

Publications

1. J. Ahlström, R. Larsson. Modeling of Distortion during Casting and Machining of Aluminum Engine Blocks with Cast-in Gray Iron Liners. Materials Performance and Characterization, 9 (5) pp. 1–19.
2. G. Ljustina, R. Larsson, and M. Fagerström. A FE based machining simulation methodology accounting for cast iron microstructure. Finite elements in analysis and design, 80:1–10, 2013.
3. G. Ljustina, M. Fagerström, and R. Larsson. Hypo and hyperinelasticity applied to modeling of compacted graphite iron machining simulations. European Journal of Mechanics - A/Solids, 37:57–68, 2012.
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6. A. Malakizadi. Optimisation of Machining Operations by means of Finite Element Method and Tailored Experiments. Chalmers University of Technology. Lic Eng. Thesis, (2013).
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12. Ljustina, Goran; Fagerström, Martin; Larsson, Ragnar (2012) Hypo– and hyperinelasticity applied to modeling of compacted graphite iron machining simulations . European Journal of Mechanics - A/Solids, 37 s. 57-68. ISSN 0997-7538
13. Ljustina, Goran; Larsson, Ragnar; Fagerström, Martin (2012) Ductile dynamic fracture modeling using embedded strong discontinuities in CGI machining simulations . Proceedings of the 25th Nordic Seminar on Computational Mechanics.
14. Ljustina, Goran; Larsson, Ragnar; Fagerström, Martin (2011). Constitutive Modeling of CGI Machining Simulations. Computational Plasticity XI - Fundamentals and Applications. ISBN 978-84-89925-23-6.
15. Ljustina, Goran; Fagerström, Martin; Larsson, Ragnar (2011) Hypo- and hyperinelasticity applied to modeling of compacted graphite iron machining simulations . Proceedings of the 24th Nordic seminar on computational mechanics. s. 59-62. ISBN 978-952-60-4347-0 ISSN 1799-4896.
16. Mats Werke, Mikael Hedlind, Mihai Nicolescu; Geometric distortion analysis using CAD/CAM based manufacturing simulation; SPS 2014
17. Anders Olofsson, Presshärdning av kronhjul - beskrivning av nuläge och framtida hjälpmedel; KT-kluster-konferensen, Katrineholm 2013
18. Process modelling using upstream analysis of manufacturing sequences; Mats Werke,
19. Mats Bagge, Mihai Nicolescu, Bengt Lindberg; to be published in International Journal of Advanced Manufacturing Technology
20. Effect of Hardenability and Press Quenching on Distortion of Crown Wheels; Albin Stormvinter, Hans Kristoffersen, Anders Olofsson, Karin Biwersi, Sven Haglund; 5th International ASM conference of thermal process modelling and simulation (2014)
21. Development of prediction tool for press hardening of crown wheels - planned to be presented at IDE 2015.
22. Project report: Press quenching of crown wheels – Development of Prediction tool - Confidential

7. Conclusions and future research

In WPA, we established a concept for performing thermo-metallurgical-mechanical calculations of press quenching of crown wheels. This concept relies on experimentally determined heat transfer coefficients modified to fit a simplified 2D geometry. A prediction tool for how the pressing forces affect the distortion of crown wheels has been developed. It is based on a combination of FEM-simulations and data from the crown wheel production. In WPB, a main result is the identification of the innovation agenda targeting cast iron machinability. The agenda covers results on material modeling, parameter identification material models based on the developed sliced cylinder concept. Using the prototype tool of the agenda, we carried out predictions of cutting forces for a class of cast iron. In these predictions, we emphasized the observed qualitative reduction of cutting force the cutting speed is increased. We also note the increase of cutting force with cutting depth as well as with nodularity approaching the CGI-type. The important message from the predictions of the agenda is that it is possible to make virtual variations in the cast iron materials and to make qualitative judgments of cast iron machinability in terms of cutting forces.

Future activities are planned regarding developing methods for incorporating the effect of casting shape and forging method in 3D-modelling. This can be done using different approaches. One important aspect is to develop a method for quantifying the grain flow pattern from up-stream operations. From the steps taken in the innovation agenda for cast iron machining, we have learnt what is working and what is not working. Obvious future development for continued work involve advancements of the proposed FE based inverse model parameter method and the development of a FE mesh insensitive material model including ductile fracture. In addition, we need to further extend the innovation agenda with respect to a wider class of materials of industrial relevance and 3D simulations.

8. Participating parties and contact person

Participating parties in WPA has been: Hans Kristoffersen Swerea IVF, Albin Stormvinter Swerea IVF, Mats Werke Swerea IVF, Sven Haglund Swerea KIMAB, Johannes Gårdstam Swerea KIMAB, Stefan Jonsson KTH, Mihai Nicolescu KTH, Anders Olofsson Scania, Karin Biwerzi Scania, Mats Bagge Scania, Solmaz Sevin Bodycote Heat Treatment, Kristian Berggren EFD Induction. Participating parties of WPB has been: Ragnar Larsson Chalmers - TM, Lars Nyborg Chalmers – MoT, Håkan Sterner VCC Skövde, Johan Ottosson AB Volvo.

Project leader was Professor Ragnar Larsson, Department of Applied Mechanics, Chalmers University of technology.