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FFI Sustainable gear transmission realization

Project within FFI Sustainable production technology

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Content

FFI in short

1. Executive summary

Gear transmission products are strategically important key components in powertrains produced by the Swedish automotive industry. Roughly on fifth of the global production of transmission products for heavy vehicles takes place in Sweden. To meet the increasing environmental and sustainability demands, the vision with a year 2025 perspective is 30% stronger and lighter automotive gearboxes with near 100% transfer efficiencies using environmentally adapted lubricants and coatings. This requires robust design and manufacturing processes. Demands for low cost, environmental impact and energy consumption are climbing and the project targeted these by adopting a holistic approach considering all critical factors in gear manufacturing. Accordingly, the project was organized in six workpackages:

- WP1 Project coordination and result dissemination
- WP2 Gear service life efficiency
- WP3 Gear materials
- WP4 Robust design and manufacturing
- WP5 Cutting tools
- WP6 Process planning

Important results obtained are:

- Gear flanks manufactured using either gear honing or green-shaving are preferable to grinding with respect to running-in and static load carrying capacity.
- Polar machinability diagrams can be used to understand the variations in machinability of case hardening steel with different microstructures.
- The variation in surface topography inherent in the manufacturing method is an important factor for the contact condition in the early life of gears.
- A 3-component dynamometer system for hobbing has been developed and is ready for testing in production machine tools.
- The main wear mechanisms observed during the experiments with the developed single tooth milling (STM) method were crater and flank wear on the primary and secondary cutting edge, respectively.
- Experimental results showed that the part of hardness on a commercial cutting insert with a TiAlN coating, boosted by the compressive residual stress, was clearly lower at the edge than on a plane surface.
- Material transfer experiments showed that at high sliding speed the tool coatings failed due to lacking mechanical support, sometimes because the generated heat caused thermal softening of the substrate. AlCrN were shown to protect slightly better against thermal softening than traditional TiN.
- Design of experiments (DoF) is shown to be a proper method capable of examining the complex process of press quenching. DoF in combination with Monte Carlo simulation is one way to support process planning regarding deeper process knowledge and proper tolerancing.

2. Background

In Sweden more than 5000 people work with production of transmissions and the production value of these is about 12 billion SEK per year. Approximately one fifth of the global production of transmission products for heavy vehicles takes place in Sweden with a strong concentration in the Mälardalen region. Transmission components certainly have a relatively high processing value, but gear manufacturing is also a complicated business that requires costly investments. Swedish automotive companies have always been strong in designing and producing high quality gear systems in-house, which is reflected by Swedish gear makers having achieved major roles on the international gear market. Today however, the ability to respond to new requirements, like those of sustainable technology and environmental concerns, will determine their future at the increasingly competitive global market.

Gears are used in nearly all applications where power transmission is required. A further testimony to the importance of gears and transmission components is that roughly a quarter of the manufacturing cost of personal cars and trucks is related to transmission components.

While gear performance improvements have been levelling off in recent years new technology points to even greater performance enhancements. These enhancements go hand in hand with the overall efforts made to achieve sustainable technology as they allow for greater durability in more compact gear packages with negligible operational noise and near 100% energy efficiency.

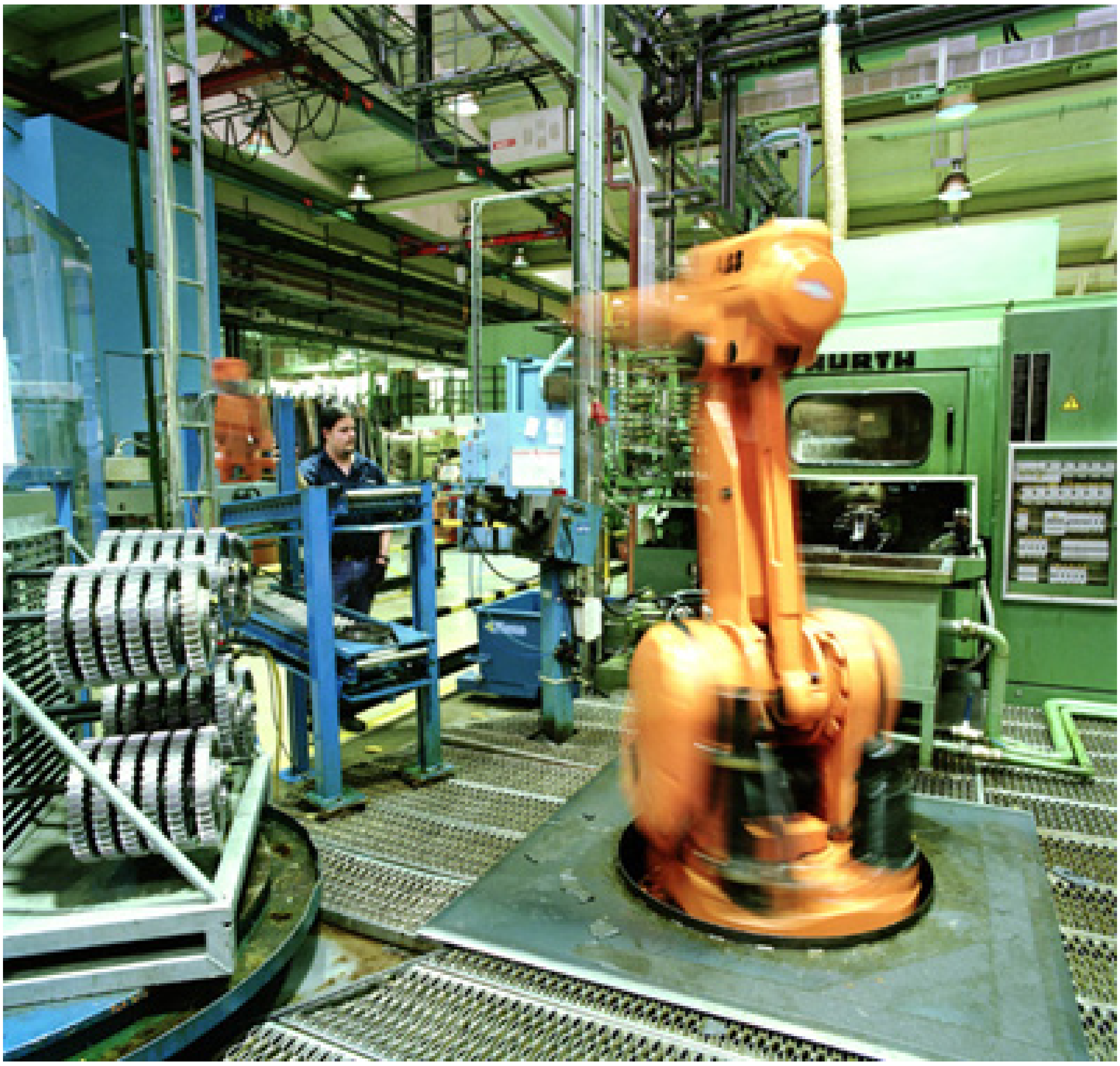

Figure 1 Transmission workshop at Scania.

To meet the increasing environmental and sustainability demands, the vision with a year 2025 perspective is 30% stronger and lighter automotive gearboxes with near 100% transfer efficiencies using environmentally adapted lubricants and coatings. This requires robust design and manufacturing processes.

Without doubt, gears are among the most critical components in all automotive vehicles. Properly designed and manufactured, they can operate at a very high efficiency and they will remain highly important parts of vehicle transmissions regardless of the energy source or propulsion principle used.

Today, however, the traditional list of requirements regarding size, strength and wear resistance is been extended to include requirements also for more silent and more robust gears. From a manufacturing point of view, the new demands require improvements of the product without increasing manufacturing costs. The ability of Swedish gear manufacturers to respond swiftly to these trends and driving forces will determine their success or failure at the international arena. Success will require new technology such as innovative gear designs, enhanced gear materials, and advances in manufacturing and automation. Increased collaboration among gear designers, manufacturers, end users and academia, supported by the Swedish government, accelerates and improves the efficiency of such technology development.

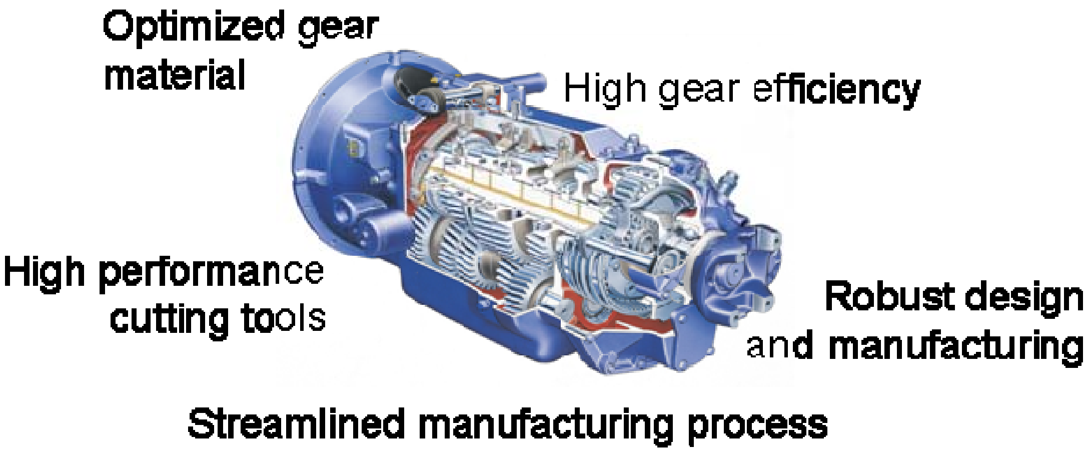

Figure 2 Future challenges in gear system realization.

The realization of a gear system is a complex process not only with respect to the gear geometry, its surface treatment and lubrication, but also considering the various operations involved in the production of them. Material selection and optimization at micro and macro level is important as gears tend to be made as small and compact as possible. Consequently, gears will be subject to high mechanical and thermal stresses and, in order to survive, only high quality materials can be used. Such materials affects the process planning considering various manufacturing operations, including manual operations, optimization of tool edges, selection and optimization of tool coatings, selection of manufacturing processes involving high precision machine tools, and economical aspects such as cost and profit which all have to be considered as well.

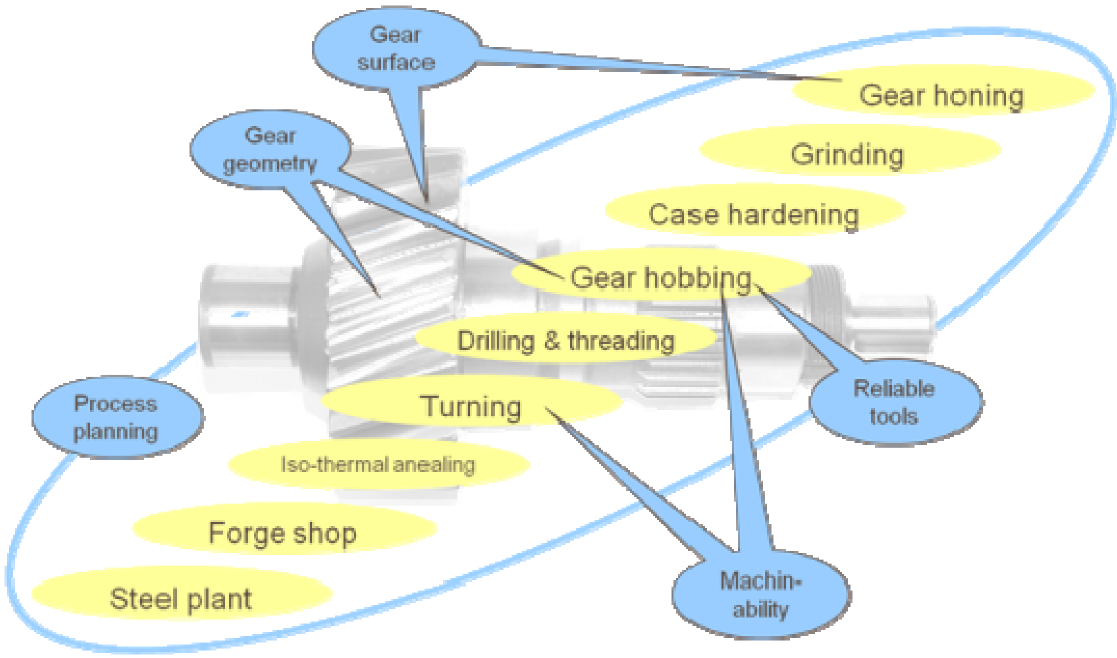

Figure 3 Complex process chains for gear manufacturing.

3. Objective

The project was expected to bring new insights to the relations between gear performance, lubricant formulation and energy losses in transmissions. It should clarify what different finishing steps can promise in terms of gear efficiency. Furthermore it should clarify what kind of modifications on gear surfaces is necessary when introducing environmentally adapted lubricants in gear boxes. The project should provide new tools for process planning and guidelines on how to achieve robust gear manufacturing. At the same time the influence of and the influence on other aspects of gear manufacturing should be clarified. New tool designs and guidelines for materials selection in tools as well as gear materials should be developed.

4. Project realization

Demands for low cost, environmental impact and energy consumption are climbing and the project targeted these by adopting a holistic approach considering all critical factors in gear manufacturing.

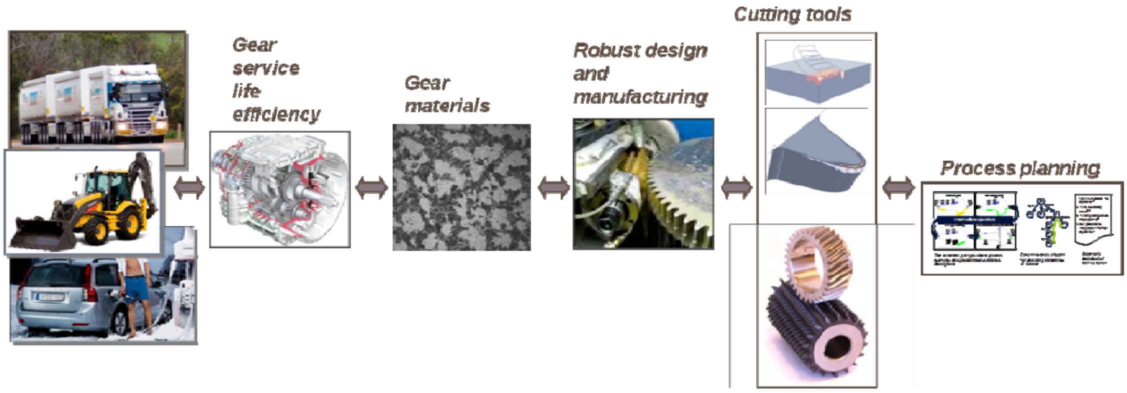

Figure 4 Holistic approach to gear manufacturing.

Accordingly, the project was organized in six workpackages:

- WP1 Project coordination and result dissemination
- WP2 Gear service life efficiency
- WP3 Gear materials
- WP4 Robust design and manufacturing
- WP5 Cutting tools
- WP6 Process planning

5. Results and deliverables

5.1 Delivery to FFI-goals

Significant reduction of fossil CO_2 and other emissions from safe road vehicles and machinery by creating conditions for manufacturing of innovative environmentally friendly and safe products.

WP2 Gear service life efficiency

- Manganese phosphate coated surfaces have a higher wear rate but have positive influence on how the lubricant adheres to the surfaces.

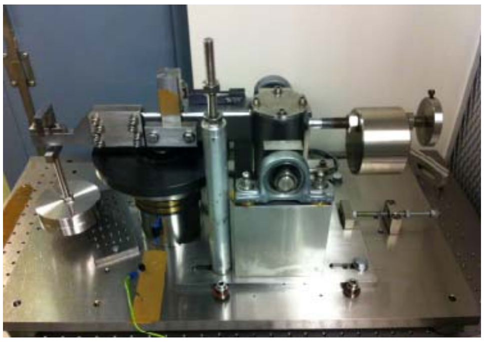

Figure 5 Tribometer for comparing ground and phosphated surfaces.

- Gear flanks manufactured using either gear honing or green-shaving are preferable to grinding with respect to running-in and static load carrying capacity. A methodology to differentiate between different surface topographies of gear surfaces has been proposed, to be used as a complement to traditional surface metrology.

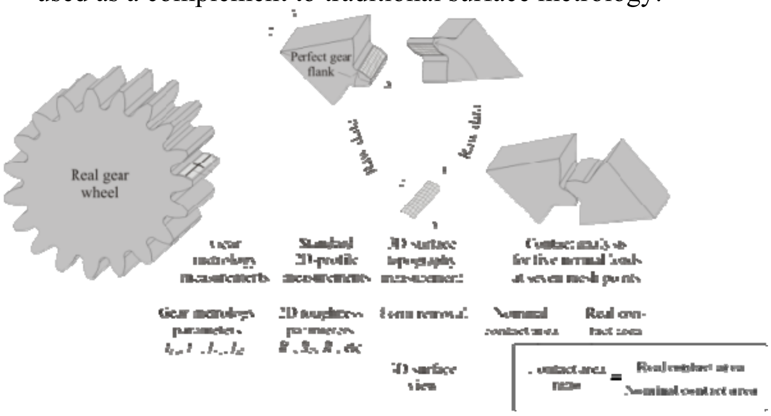

Figure 6 The real contact area ratio to describe the contact conditions.

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WP 4 Robust design and manufacturing

Figure 7 gives an overview of gearing systems at different scales: a gear pair in contact, a close-up of two gear surfaces in contact with deviations from a perfect gear profile, and surface active additives adsorbed with the polar end on a metal substrate. This workpackage covered the whole spectrum, although with a focus on the small scale of gearbox tribology.

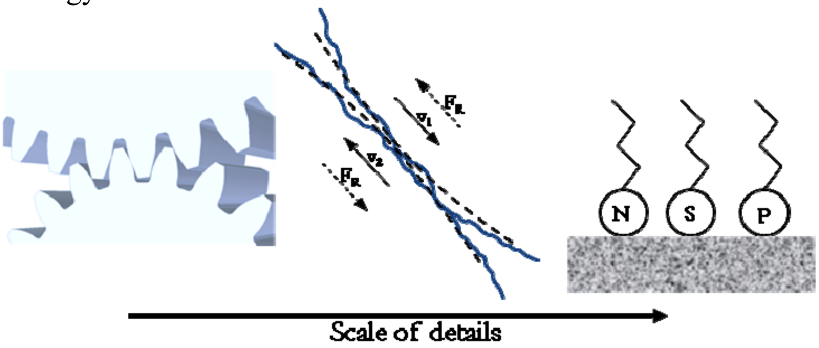

Figure 7 Scale of details ranging the contacting surfaces on a macro to micro level and finally the contact boundary layers on a nano level.

- It has been shown, by experimental work and computer simulations, that the variation in surface topography inherent in the manufacturing method is an important factor for the contact condition in the early life of gears.
- A stylus instrument has been used to measure four gears manufactured by hobbing, plunge green-shaving, power-honing, and generating grinding. Surface analysis revealed that the formation and composition of surface boundary layers depends strongly on the chemical composition of the lubricant, but also on pre-existing surface boundary layers. Additionally, surface boundary layers play a major role in frictional behavior, wear and in allowing the lubricant to react properly with the surfaces.

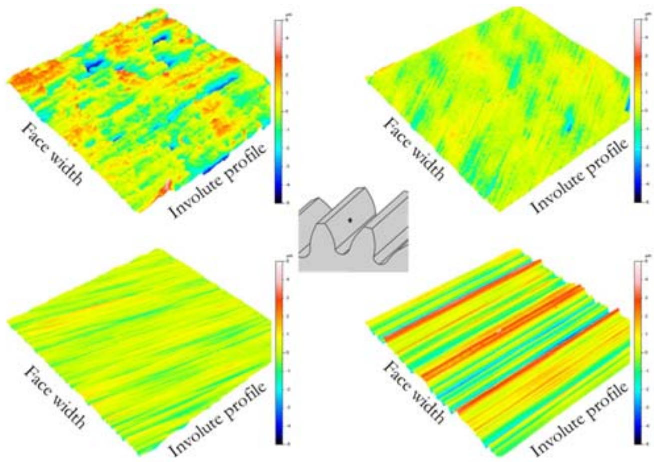

Figure 8 Surface topography of four common manufacturing methods. The 1 x 1 mm areas have had the form removed by a fifth degree 3D polynomial. All topographies make use of the same height scaling: -5 to 5 µm.

Product requirements in terms of lighter weight and increased passive safety, which in turn requires new or improved materials and manufacturing processes, are complied with.

WP3 Gear materials

The main conclusions from the studies on machinability of case hardening steel are:

- Materials with smaller pearlite nodular size exhibit less tool wear (higher B_{index}) as compared to large nodular pearlite due to small grain size.
- Tool wear is more affected by pearlite nodular size and pearlite content than by hardness and pearlite morphology.
- Material with larger nodular pearlite (LNP) has a lower critical feed which leads to more segmented chips and better chip breakability.
- Manganese sulfide (MnS) inclusions are beneficial and increase chip breakability. Precipitates such as carbides are detrimental and have to be controlled with proper heat treatment.
- Polar machinability diagrams can be used to understand the variations in machinability of case hardening steel with different microstructures.

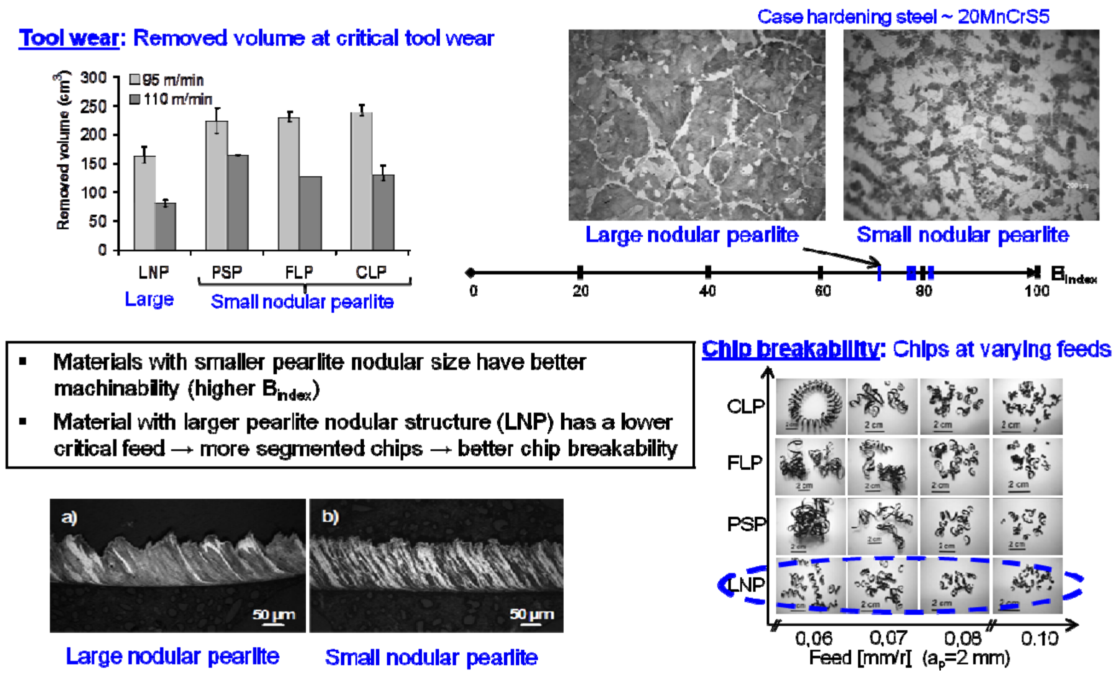

Figure 9 Summary of conclusions.

Recommendations:

- It is very important to perform controlled and uniform heat treatments before machining of case hardening steels.
- The microstructure has to be well designed by considering tool wear and chip breakability. That means, it is essential to obtain a uniform microstructure with optimized grain size and phase content.
- For better tool wear and chip breakability, the optimized case hardening steel should contain approximately equal amounts of ferrite and pearlite and should have large grain size (about 50 to 100 µm). Hence, it is necessary to choose proper heat

treatment parameters such as austenitization temperature, holding time and temperature in order to obtain desired microstructure.

- Polar machinability diagrams can be used to compare and describe machinability for different microstructures.

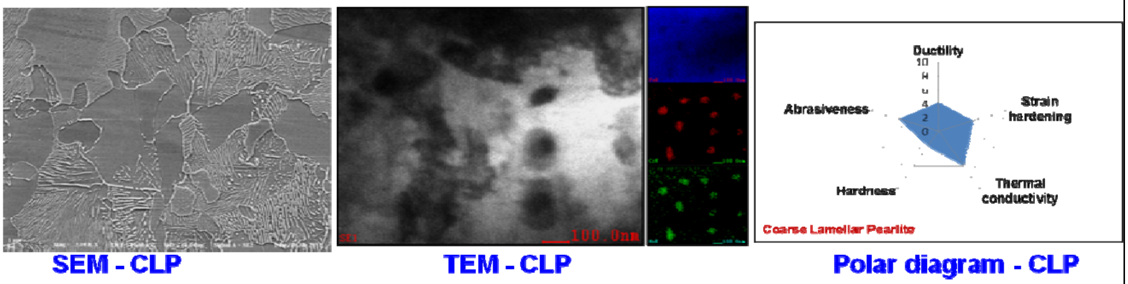

Figure 10 Illustration to recommendations.

WP4 Robust design and manufacturing

When producing high precision gears it is important to identify the effects of manufacturing variations on the gear functional requirements. Manufacturing variations can include individual machine variations (caused by for example tool wear), lack of rigidity of the workpiece and the choice of manufacturing method. Most research made on gear manufacturing variation influence on the gear performance is related to the standard gear parameters (e.g. geometry), but not how different manufacturing processes affect other properties (e.g. material microstructure) for the finished product. A dynamometer fixture for three 3-component force sensors located at 120° on the base of the fixture has been developed. The workpiece (gear) is clamped on the fixture, which is rotating simultaneously with the hobbing tool in order to generate the gear teeth.

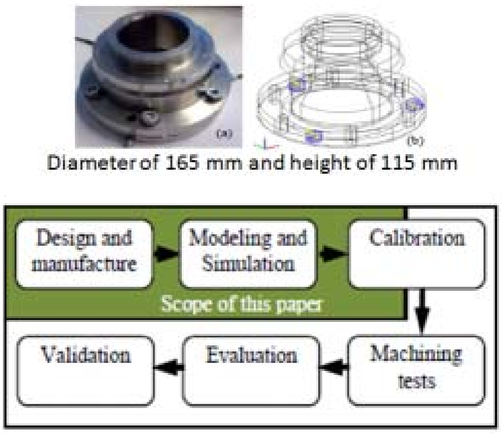

Figure 11 Dynamometer system for hobbing.

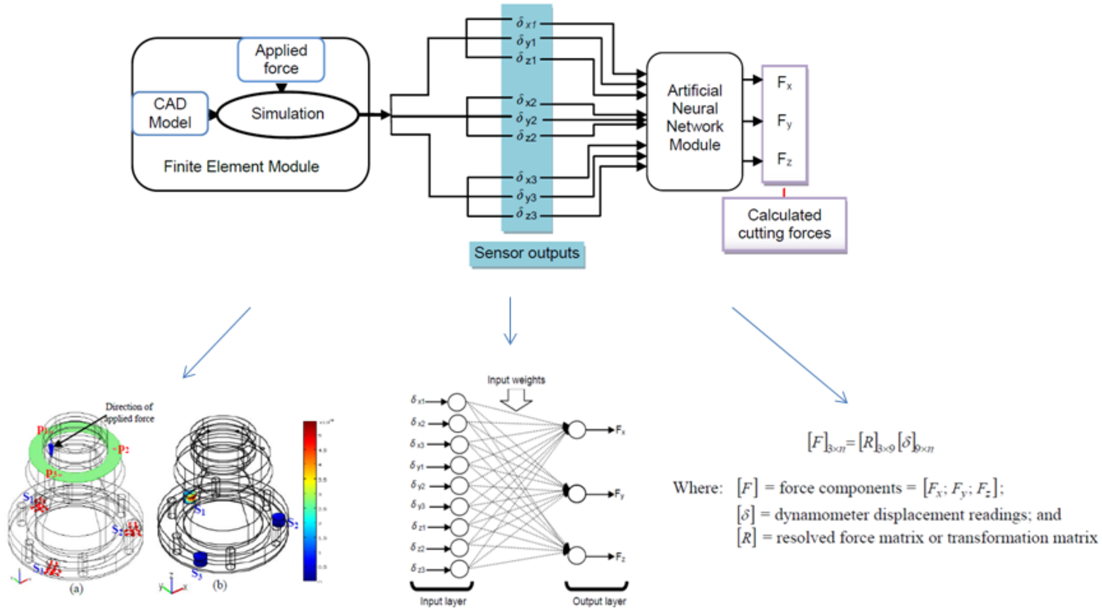

Figure 12 Model concept.

The computed resultant component of the cutting force is then transmitted by a wireless system to a signal acquisition system to record the cutting force variation during hobbing. The wireless system is designed with 6 channels, thus besides force components, also temperature and strain on the hobbing tooth can be evaluated. Good correlation between direct and wireless measurements has been shown. The 3-component dynamometer system for hobbing is ready for testing in production machine tools.

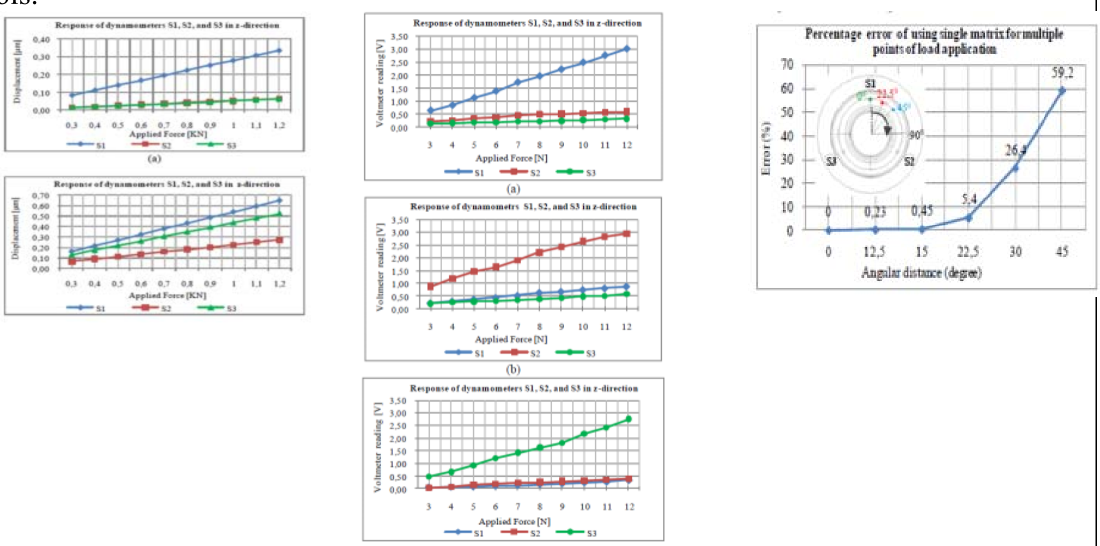

Figure 13Simulation results (left), experimental results (middle) and calibration error (right).

Figure 14 The system components.

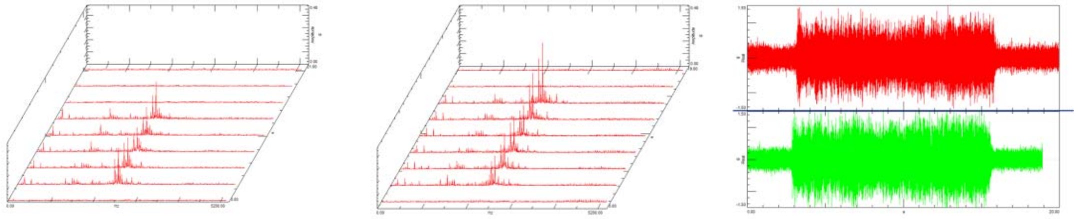

Figure 15 Direct measurement (left), wireless measurement (middle) and direct (red) and wireless (green) measurements (right).

40% higher productivity in production planning.

WP6 Production planning

Gear production is an area where the process planning is highly important due to the close relationships between gear design and manufacturing methods. Gear geometries are associated with complicated generating kinematics. Machining and measuring possibilities define what the gear designer has to deal with. The complete gear part (gearwheel, shaft *etc*.) is produced using both machines and tools that are specially developed for gear manufacturing, and with standard machine tools for common methods like turning, hardening and grinding. It is a symbiotic development of gear design and gear manufacturing methods aimed to achieve high performance gears and efficient processes. This implies the need for process planning tools and methods which can manage the characteristics of gear part production.

The role of a process planner can briefly be described as a link between design and manufacturing. The responsibility is to establish and maintain good connections for interchanging and solving technical problems concerning production. The goal is to reach solutions that satisfy both design requirements and prerequisites for sustainable production. A process planner must, in that respect, be the expert and speaking partner concerning manufacturing (Figure 16).

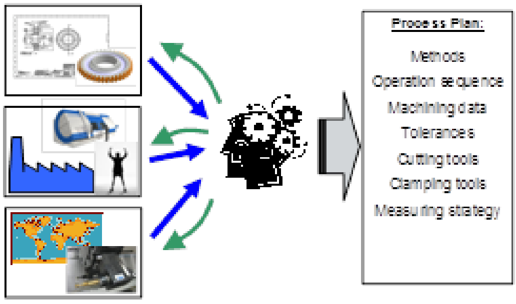

Figure 16 The interaction of a process planner.

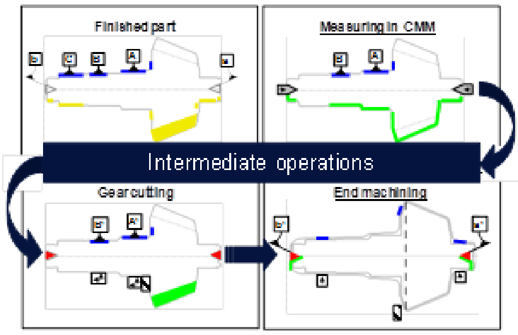

Figure 17 Framework for visual representation of systematic process planning.

The approach for systematic process planning earlier presented in MERA KUGG (Figure 17) aims to support the possibilities to structure, identify, examine and evaluate details step by step but with a good overview. It will also facilitate easier process planning when single or extensive changes are introduced on a product or in a manufacturing process. In addition to the possibilities to establish documentation of the technical reasoning this will provide a way to describe the process planning work. The substance of the methodology is mainly derived from process planning experience and put into a structured context aimed at satisfying the objective of this research.

The approach for systematic process planning did not include tolerancing, where process behavior and capability is balanced with the need (Figure 18). The most important work done in this workpackage is about how complex processes can be examined with the purpose to define relevant, and well-balanced, tolerances.

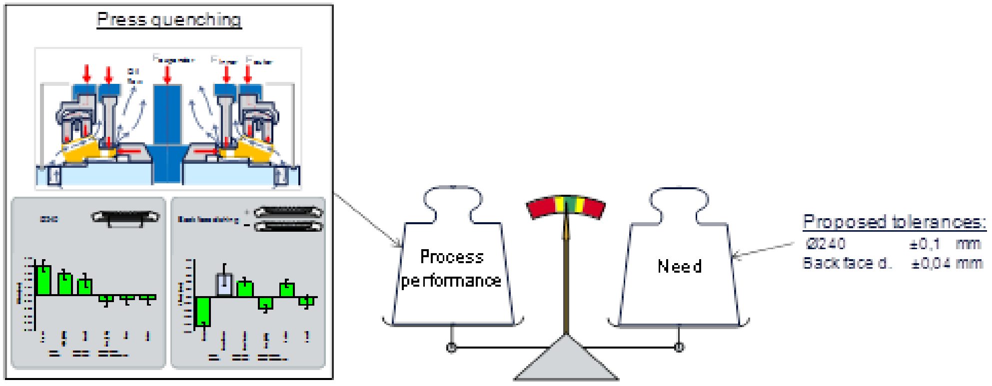

Figure 18 Balancing need and process performance.

The approach to find out what controllability and performance you can get from a certain process is the use of design of experiments (DoE). The results from experiments done on press quenching shows how a couple of factors significantly affects both the size and shape of bevel gear parts. These factors are of two types; controllable, *e.g.* pressure settings, and uncontrollable, *e.g.* material.

The results from the evaluation of the experiments include not only a regression model, which describes the impact of different factors on the size and shape, but also measures of the process variations. By using the measures of process variations and applying Monte Carlo simulations on the regression model outcomes of the process are estimated. These estimations can be done for different scenarios where combinations of machine setups, materials and factor settings are tested. Finally tolerances are defined by evaluating how well the estimated outcome of the process fulfills the required capability or number of defect parts.

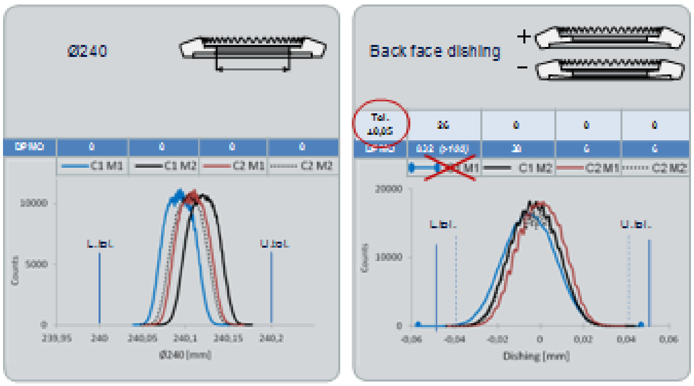

Figure 19 Estimated outcomes of the press quenching process in relation to proposed tolerances.

Design of experiments is shown to be a proper method capable of examining the complex process of press quenching. This is proven by the capacity of the regression models to predict results for Ø240 and back face dishing. Design of experiments in combination with Monte Carlo simulation is one way to support process planning regarding deeper process knowledge and proper tolerancing.

30% higher productivity in production processes.

WP5 Cutting tools

Single tooth milling (STM)

It is important to have good control of defects in both coating, steel substrate as well as in the interface between the coating and the HSS material to reach high tool reliability. Cutting edge geometry and surface roughness before and after coating deposition are crucial factors for the propagation of wear. Using hobs for such studies involves high production costs of tools, expensive machine costs as a gear hobbing machine is required and time consuming wear tests. A single tooth milling test (STM) can be used to reproduce the wear mechanisms on hobs by using adequate cutting data translated to the milling operation.

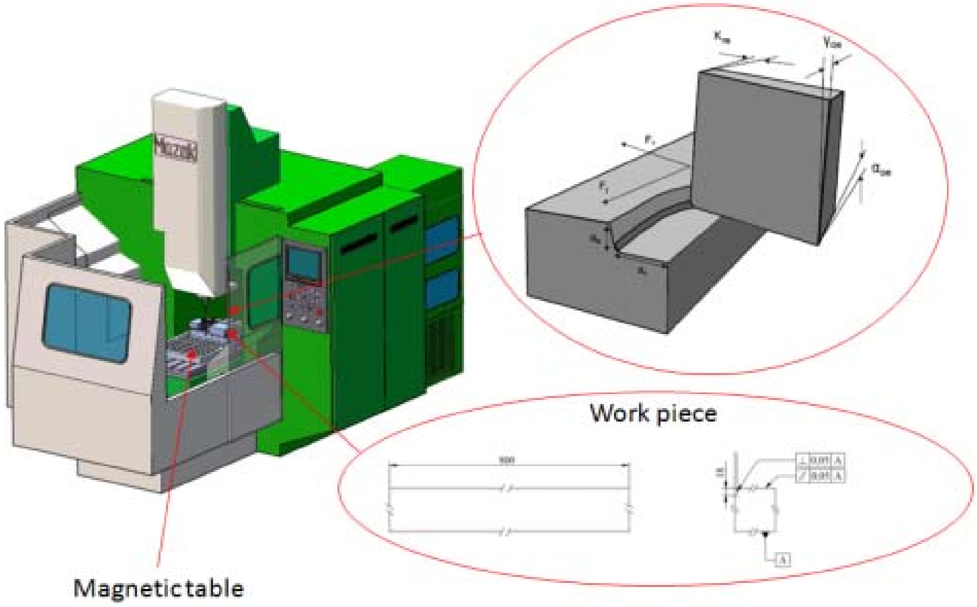

Figure 20 Test setup for STM method in a conventional machining center.

Conclusions:

- The main wear mechanisms observed during the experiments in STM were crater and flank wear on the primary and secondary cutting edge, respectively.
- Regarding the flank face wear, a trend can be distinguished, see Figure 21. With increasing edge radius, the size of the flank face wear becomes smaller due to the internal stress of the tooth coating, which apparently decreases with an increase of the cutting edge radius. The loss of edge volume is related to the edge radius and the surface roughness, respectively.

Figure 21 Flank wear for one of the tool specimen groups investigated.

- An increase in the edge radius has a positive effect on the decreasing of the loss of volume, while a rougher surface causes an increased loss of volume. A situation of severe flank wear involves a great risk for heat transfer into the tooth substrate, which results in a tooth break-down.
- An increased edge radius leads to an increased curvature of the chips, which in turn results in a decreased contact area. The surfaces roughness exceeding 0.4 µm, favors development of formed, so-called oxidized layers at an early stage.
- An increased edge radius gives also rise to a stagnation zone on the edge, which influences the shear process during the chip formation. The width of the second deformation zone will be affected by a tendency to increase with increased radius. The influence of the surface roughness on the second deformation zone is not as obvious, a fact that might depend on the extent and the distribution of the seized and the sliding regions that mainly involve the contact surface on the rake face.
- The scores or ridges that might remain after the grinding process are detrimental to the strength of the tooth and are in many cases the basis for the propagation of cracks. In the case of irregularities left on the tooth surface when the coating is deposited, polishing then involves a strong reduction of the thickness of the layer on higher areas on the surface, which greatly impairs the protection of the tooth substrate.
- The extent of local chippings seems to increase with surface roughness.

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Residual stress

Residual stress in coatings is a natural consequence of the deposition process used for applying the coatings on the cutting tools. For hobs, the quality and properties of the coating play important roles in the performance of the tool. Certain PVD processes give coating surfaces, which in microscope as in Figure 22 are seen to contain large amounts of droplets coming from the deposition process. These should if possible be avoided as they constitute weak points of the coating where residual stress within the coating, and external stress during cutting, can cause local damage that grow from isolated damage to extensive damage of the tool.

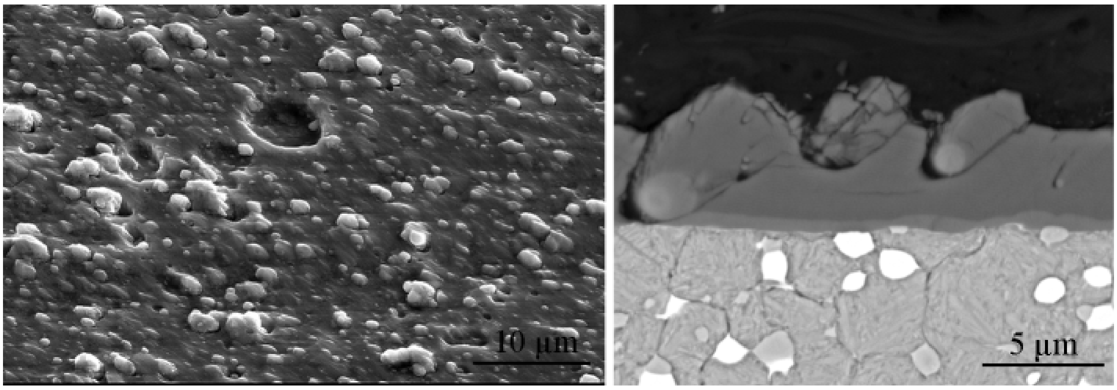

Figure 22 An as-deposited coating surface of a cutting tooth in plane view (left) and in cross section (right).

Another stress related effect is that compressive residual stress induces lifting stress at sharp edges, *e.g*. on cutting edges. These promote delamination at the edge, already during deposition, after cooling or during cutting, see Figure 23. These lifting stresses do not exist on flat substrate surfaces but at an edge they increase as the cutting radius is decreased, as shown in the modeling results in Figure 24 (left). A flat surface has infinite radius and for that case the h/R becomes zero and that results in $\Delta\sigma_{nn}=0$, but as the radius increase the lifting stress increase. This is modeled for a TiAlN coating with a nominal residual stress of -1.7 GPa deposited on HSS. Clearly, thick coatings on sharp edges must be avoided to not risk delamination at the cutting edge.

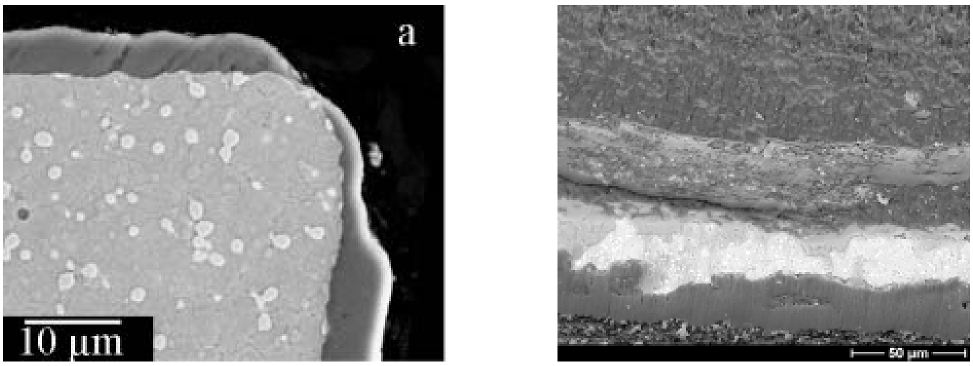

Figure 23 An unused tooth of a hob in a cross-section showing coating damage at the cutting edge (left) and a cutting edge after use with extensive wear at the edge, initiated as edge chippings, and crater wear at the rake face (right).

A further effect originating in the residual stress is the beneficial effect of stress enhanced cohesion in the coating, *i.e.* the effect the coating manufacturer utilize to improve the performance of the coating. This effect is not fully effective at the very cutting edge as the edge is somewhat elastically relaxed and the compressive residual stress is locally reduced. Also this was modeled as shown in Figure 24 (left). The $\Delta\sigma_{tt}$ increase, *i.e.* the stress parallel to the interface is reduced, as the *h/R* ratio is increased. Also from this reason, thick coatings and sharp edges should be avoided if the beneficial effect of "artificial" cohesion is to be utilized.

The residual stress at a cutting edge cannot be directly measured using the otherwise common method of X-ray diffraction. Instead, the effect was illustrated using a method where hardness is used as a indicative measure of the residual stress. A commercial cutting insert with a TiAlN coating, having a residual stress of -1.7 GPa, was used. The hardness of stress relieved pillars, see Figure 24 (right), was compared to the hardness of as-deposited coating close by. On a plane surface the drop in hardness, due to the stress relief in pillars, was 2.6 GPa whereas the drop at the cutting edge was only 1.6 GPa. This shows that the part of hardness, boosted by the compressive residual stress, was clearly lower at the edge than on a plane surface.

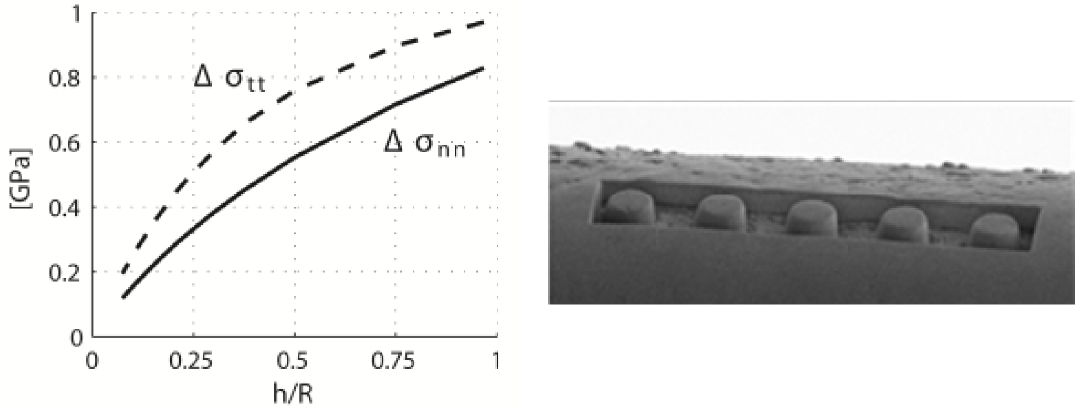

Figure 24 Modeled edge effects on the residual stress in a coating with a plane residual stress of -1.7 GPa (left). Stress relieved pillars at the cutting edge was used to illustrate the locally reduced residual stress at the very cutting edge (right).

Material transfer

It is well known that material transfer from the work material to the tool surface occurs in metal cutting, and that it influences the cutting edge geometry, the damage mechanisms of the cutting tool, as well as the surface quality of the machined component. The amount of transfer, and the nature of the transferred material, depends on the cutting parameters and the work material and the tool itself. For this reason studies of the initial material transfer to different coatings are important.

Cylinders with different coatings and different surface roughness were tested at different sliding speed to investigate the initial material transfer from the work material to the tool surface. It was shown that independent of coating material, the material transfer had the same nature. Also the friction coefficient was very similar. At low sliding speeds, steel transferred in an oxidized state all over the contact. At moderate sliding speed the central part of the contact, experiencing the highest temperature and pressure, developed a layer composed of Al, Si and Mn in oxidized form, see Figure 25. Further out from the centre of the contact, steel was transferred in an oxidized state. At high sliding speed the coatings failed due to lacking mechanical support see Figure 26, sometimes because the generated heat caused thermal softening of the substrate. AlCrN were shown to protect slightly better against thermal softening than traditional TiN.

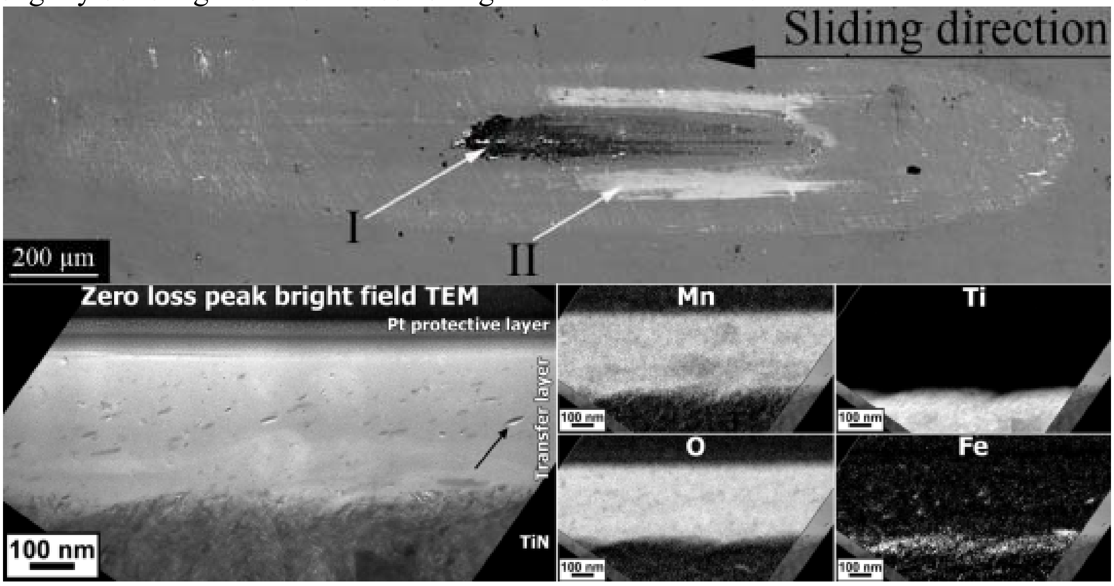

Figure 25 Overview of the contact on the TiN coated cylinder having sliding against the case hardening steel (top). Cross section through the central transferred layer with Mn and O exemplifying the oxide content on top of an initially transferred iron rich layer (bottom).

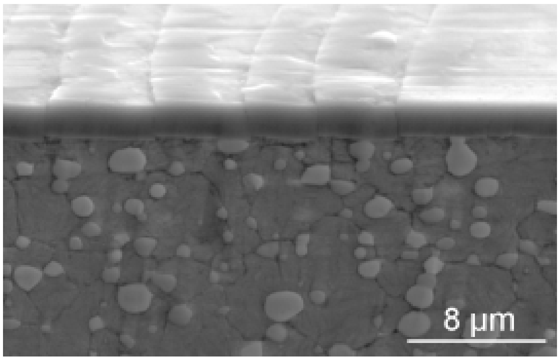

Figure 26 Excessive loading of the TiN coating caused plastic deformation of the substrate and through thickness cracking of the coating.

6. Dissemination and publications

6.1 Knowledge and results dissemination

An efficient and appreciated result dissemination activity has been the recurrent gear meetings, inherited from the MERA KUGG project. The gear meetings were scheduled as follows:

- Day 1 late afternoon and evening: steering group meeting followed by a gear dinner.
- Day 2 morning and early afternoon: plenary gear meeting with presentations from researchers in the project, and company partners as well as invited speakers from both Swedish and international research organizations and companies.
- Day 2 afternoon: company tour or lab visit.

The tradition with gear meetings is considered as an important networking as well as knowledge and experience transfer activity and will be maintained in the ongoing FFI SMART project. The plenary part is open also for participants not involved in the project.

A gear wiki for the industry with practical advices and diagram has been set up: 130.237.56.41/mediawiki/index.php/Hållbar_framtagning_av_kuggtransmissioner.

The project results are also reported in a wiki: 130.237.56.41/mediawiki/index.php/FFI_Sustainable_gear_transmission_realization.

6.2 Publications

Bagge, M, 2009, An approach for systematic process planning of gear transmission parts, licentiate thesis, KTH Royal Institute of Technology, TRITA-IIP, ISSN 1650-1888; 09-01, Stockholm.

Bergseth, E, Björklund, S, 2009, Logarithmical crowning for spur gears, submitted to Journal of mechanical engineering special issue for ECOTRIB 2009 and presented at ECOTRIB 2009 2nd European conference on tribology, June 7-10, Pisa.

Bergseth, E, 2009, Influence of surface topography and lubricant design in gear contacts, licentiate thesis, KTH Royal Institute of Technology, TRITA-MMK 2009:18, Stockholm.

Björkeborn, K, Klement, U, Lenander, A, 2009, Study of machinability of case hardening steel in production environment, Proceedings of the Swedish Production Symposium – 2009.

Gerth, J, Larsson, M, Wiklund, U, Riddar, F, Hogmark, S, 2009, On the wear of PVD-coated HSS hobs in dry gear cutting, Wear 266 (3-4), pp 444-452.

Gerth, J, Werner, M, Larsson, M , Wiklund, U, 2009, Reproducing wear mechanisms in gear hobbing – Evaluation of a single insert milling test, Wear 267 (12) , pp 2257-2268.

Sjöberg, S, Sundh, J, 2009, Scuffing resistance of gear surfaces influence of manganese phosphate and lubricants, submitted to Journal of mechanical engineering special issue for ECOTRIB 2009 and presented at ECOTRIB 2009 2nd European conference on tribology, June 7-10 2009, Pisa.

Werner, M, 2009, Investigation on HSS milling inserts, licentiate thesis, KTH Royal Institute of Technology, TRITA-IIP, ISSN 1650-1888; 09-03, Stockholm.

Bergseth, E, Björklund, S, 2010, Logarithmical crowning for spur gears, Journal of Mechanical Engineering 56 (2010) 4.

Bergseth E, Olofsson U, Lewis R, Lewis S, 2010, Effect of gear surface and lubricant interaction on mild wear, Presented at Tribology Congress in Australia ASIATRIB 2010, 5-9 December 2010, Perth, Western Australia (konferensbidrag), inskickat till Tribology Letters.

Björkeborn, K, Klement, U, Oskarson, H-B, 2010, Study of microstructural influences on machinability of case hardening steel, International Journal of Advanced Manufacturing Technology, 49 (2010) 441-446.

Gerth, J, Larsson, M, Wiklund, U, 2010, Examination and classification of damage mechanisms on PVD coated HSS hobs used in Swedish gear manufacturing industry, Submitted to Tribologia, 2010.

Nyberg, H, Gerth, J, Olofsson, J, Wiklund, U, Jacobson, S, 2010, On the influence from micro topography on the structure and growth of low friction amorphous carbon PVD coatings, PSE 2010, Garmisch Partenkirchen, September 13-17, 2010.

Sjöberg, S, 2010, On the running-in of gears, licentiate thesis, KTH Royal Institute of Technology, Stockholm.

Alazar, S A, Werner, M, Nicolescu, C M, 2011, Development of cutting force measurement system for gear hobbing, Proceedings of the ASME 2011 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference, IDETC/CIE 2011, August 28-31, 2011, Washington, DC, USA, DETC2011-48121.

Gerth, J, Larsson, M, Wiklund, U, 2011, Survey of damage mechanisms on PVD coated HSS hobs in Swedish gear manufacturing industry, Tribologia 30 (1-2), pp 37-50.

Sjöberg, S, Olofsson, U, Björklund, S, 2011, The influence of manufacturing method on the running-in of gears, Journal of Engineering Tribology, Proceedings of the Institution of Mechanical Engineers Part J, DOI: 10.1177/1350650111414471.

Didner, N, 2011, The running-in behaviour of gear surfaces with influence of manganese phosphate, master of science thesis MMK 2011:37 MKN 048, KTH Royal Institute of Technology, Machine Design, SE-100 44 Stockholm.

Bagge, M, Lindberg, B, 2012, Analysis of process parameters during press quenching of bevel gear parts, Swedish Production Symposium, Nov 6-8, 2012, Linköping, Sweden.

Bergseth E, Olofsson U, Lewis R, Lewis S, 2012, Effect of gear surface and lubricant interaction on mild wear, Tribology Letters, article in press, DOI: 10.1007/s11249-012-0004-y.

Bergseth E, Sjöberg S, Björklund S, 2012, Influence of real surface topography on the contact area ratio in differently manufactured spur gears, Tribology International, 56 (2012) 72–80.

Gerth, J, Heinrichs, J, Nyberg, H, Larsson, M, , Wiklund, U, 2012, Evaluation of an intermittent sliding test for reproducing work material transfer in milling operations, Tribology International, Volume 52, August 2012, Pages 153–160.

Heinrichs, J, 2012, On transfer of work material to tools, dissertation, Uppsala universitet, ISBN: 978-91-554-8261-9.

Gerth, J, Heinrichs, J, Nyberg, H, Larsson, M, Wiklund, U, 2012, Evaluation of an intermittent sliding test for reproducing work material transfer in milling operations, Tribology International 52, pp 153-160.

Heinrichs, J, Gerth, J, Bexell, U, Larsson, M, Wiklund, U, 2012, Influence from surface roughness on steel transfer to PVD tool coatings in continuous and intermittent sliding contacts, Tribology International 56, pp 9-18.

Heinrichs, J, Gerth, J, Thersleff, T, Bexell, U, Larsson, M, Wiklund, U, 2012, Influence of sliding speed on modes of material transfer as steel slides against PVD tool coatings, accepted, Tribology International

Nakhjiri, M, Study of running-in on spiral bevel gears, master of science thesis, KTH Royal Institute of Technology, Machine Design, SE-100 44 Stockholm.

Surreddi, K B, Björkborn, K, Klement, U, Microstructural characterization of chips of case hardening steels, in manuscript.

Surreddi, K B, Klement, U, Methodology for evaluating the machinability of case hardening steel by using polar diagrams, in manuscript.

Surreddi, K B, Yao, Y, Klement, U, Microstructural studies of case hardening steel and their chips, in manuscript.

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7. Conclusions and future research

The knowledge and the experiences obtained from the project in parallel with new industrial demands have laid the foundation for formulating new challenges in gear manufacturing. Thus, three important and industry relevant research issues are addressed in the new project FFI Sustainable manufacturing of future transmission parts – SMART:

- gear rolling
- machining of clean steels
- influences from hardening on form deviations.

8. Participating parties and contact person

The project partners are listed below.
Academic: KTH Royal Institute of Technology, Chalmers University of Technology and Ångström Laboratory (Uppsala University)
Automotive: Scania and Volvo
Automotive subcontractors (Fordonskomponentgruppen, FKG): Componenta Wirsbo, GKN Drivline Köping, Ionbond, Leax, Ovako Hofors and SwePart Transmission
Other companies: Albin Components, Erasteel Kloster, Höganäs, Meritor HVS, Oerlikon Balzers, Sandvik Coromant and SVA

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