FFI Sustainable manufacturing of future transmission parts – SMART

Project within FFI Sustainable production technology

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FFI

Content

FFI in short

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

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1. Executive summary

New challenges towards more environmentally friendly powertrains in future commercial vehicles put demands on performance and manufacturing of gears. Higher strength requirements enable higher possible loads to be taken in transmissions of the same size as today or that transmissions can be made more compact. In this project, we focus on two methods to make gears more high-strength, namely to replace gear milling with gear rolling based on plastic forming and the introduction of clean steels with reduced inclusion content. To take advantage of the progress of gear rolling, case hardening has to be improved so that the spread in form deviations are reduced. This can be done with better process planning methods taking into account the spread of the characteristics of incoming material and thus reduces the spread in production results.

It is possible to produce gears with high modules (eg. 4) by gear rolling method with commercial rolling machines. The quality of manufactured gears is yet not in target level for truck applications. We reach quality 11 (with no finishing) in our experiments but further improvments need more work and research. FEM is a very reliable tool in the process planning to be used for quality optimization. It is necessary to simulate the gear rolling process for a new component before investing in tools and pilot tests. With the current research results, the rolling will be expensive to reach the quality of 5-6 (after finishing process) for high modules (over 2.5 mm). The process can be used for small modules under 2.5 mm currently.

The difference in machinability of clean carburizing steels as compared to conventional carburizing steels with a sulphur content of S=0.02-0.04 wt.% is minor. Microstructural aspects are probably more important than the sulphur content. This is based on tests in rough turning and an experimental test that mimics gear hobbing. In case of the tool steel investigated alternate machining strategies may be required. Another tool grade in rough turning than the one tested would probably increase the performance significantly. Maybe more demanding is the probable need to introduce new tooling concepts in the gear hobbing process. The high speed steel substrate of conventional solid hobs becomes over tempered at the cutting edge by the higher temperature generated in the chip removal of the hot work tool steel. However, hobs made of coated cemented carbide are commercially available both with solid and indexable concepts. The machinability of clean steels can be characterized as follows: a) somewhat more adhesive in the tool-chip contact, b) somewhat more difficult chip breaking, c) somewhat more heat in the cutting zone with clean steels, d) the combination of the new generation of textured alumina CVD coatings of turning tool grades and clean steels with a minimum of abrasive oxides and a fined grained microstructure makes a tremendous potential in increased productivity and e) the minimal abrasive wear constituents of these steels makes a high and robust tool life also with PVD coated solid hobs.

Upon hardening martensite is formed, with a greater volume than the parent phase. This results in distortion, which is to some extent predictable and thus can be compensated for in soft machining. Unwanted, non systematic, changes in shape that appears after heat treatment are complex and can be caused by many factors. All steps in manufacturing the steel and manufacturing of components are carriers of distortion potential showing as distortions after heat treatment. The effect of hardenability on distortion is significant. This project has shown that distortion of simple geometries as well as industrial components is affected by hardenability, i.e. alloying content. It is important to be consistent in method how to calculate the hardenability and to follow-up variations in hardenability for different heats. Also alloying elements that are not covered in hardenability models influences on distortions, e.g, (Al, Ti, Al/N). Hardenability dependent geometrical compensation in soft machining seems feasible for reducing the detrimental effects of distortion. The compensation has to be worked out from controlled production trials and most probably independently for every steel supplier. Hardenability data provided by the steel producers seems more reliable when compared to calculations done by common methods. There is a good potential to systematically study distortions through production monitoring. Identify relevant factors and keep as many of them as possible constant and only study variations in hardenability and chemical composition. Multivariate data analysis is a useful tool.

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.

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 leveling 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 a more compact gear package with negligible operational noise and near 100% energy efficiency.

3. Objective

New challenges towards more environmentally friendly powertrains in future commercial vehicles put demands on performance and manufacturing of gears. Higher strength requirements enable higher possible loads to be taken in transmissions of the same size as today or that transmissions can be made more compact. In this project, we focus on two methods to make gears more high-strength, namely to replace gear milling with gear rolling based on plastic forming and the introduction of clean steels with reduced inclusion content. To take advantage of the progress of gear rolling, case hardening has to be improved so that the spread in form deviations are reduced. This can be done with better process planning methods taking into account the spread of the characteristics of incoming material and thus reduces the spread in production results.

4. Project realization

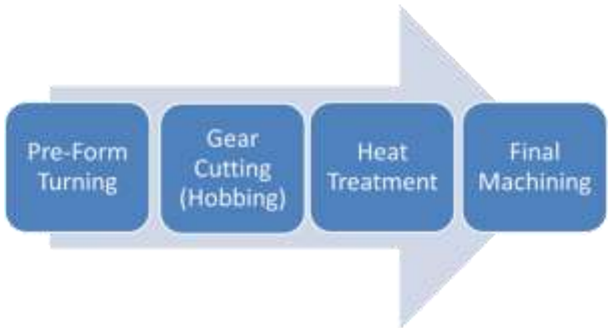
The project was divided into four work packages for project management (WP1), development of gear rolling and subsequent heat treatment (WP2), development of machining of clean carburizing steels (WP3) and studies of how the steel hardenability influence heat treatment distorsions (WP4).

5. Results and deliverables

5.1. WP2 Manufacturing of retarder axle (gear rolling and subsequent heat treatment)

Figure 1 Gear rolling.

Today the dominating manufacturing route for gear wheels for truck applications is starting with a forged blank which is turned and milled to shape, followed by heat treatment and finally hard machining, Figure 2. One interesting optional route has been introduced for passenger car applications where the milling step is replaced by gear rolling. In that manufacturing process the material removal is replaced by plastic forming. This has several advantages like material saving since no chips are produced, hardening of the material which can sometimes be sufficient for final use and shaping of material structure and defects along the tooth flank profile of the gears. The latter means that fatigue properties of the gear wheel can be improved since the defects which cause fatigue failure have more favorable orientation than after milling. In the case of small gear wheels for passenger car gear boxes these properties can be obtained with high production speeds and with good dimensional accuracy so that no additional soft machining is required before heat treatment, Figure 3.



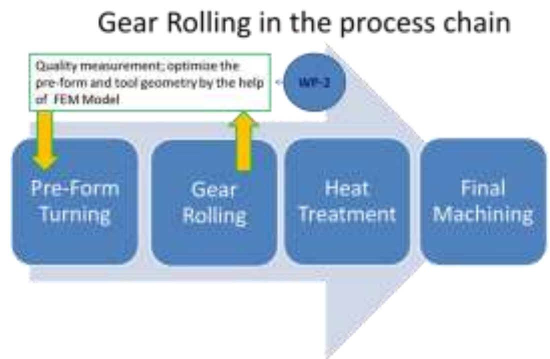


Figure 2 Conventional production chain for gear wheels.

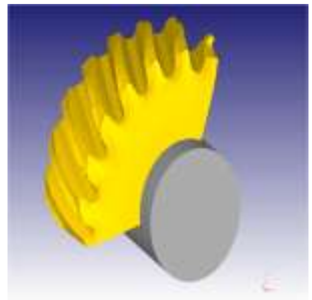
Figure 3 Production chain with gear rolling.

The good experience from gear rolling in manufacturing of small gear wheels has raised the question whether the good properties of gear rolling could also be realized for large truck gear wheels. One demonstrator helical gear wheel with a helix angle of 20°, a pressure angle of 20°, diameter 100 mm and a module of 4 mm was selected. All stages of production up to carburizing were studied. Special focus was directed to the accuracy of shape which could be obtained after gear rolling since this factor determines if subsequent machining operations would be required which would partly spoil the advantages. It was stated that an ISO quality of the gear tooth shape around 7 would be required after rolling.

After selecting the demonstrator gear wheel geometry it was decided to realize the production route both with simulation and with experimental trials. In fact it turned out that the simulations became an important part of the process planning for the experimental trials.

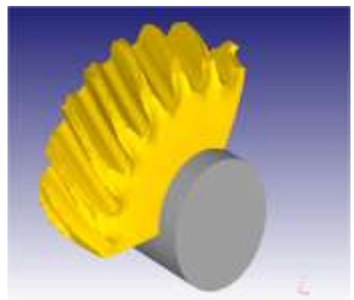
A number of gear rolling trials were performed at Fraunhofer IWU on a Rollex XL HP machine. The process conditions which were studied with the three dimensional simulations were also studied experimentally. It was found that the simulations could in a satisfactory way reproduce the trends observed in the experiments, Figure 4.

Experimental trial after a penetration of 6 mm of tool into blank.



Simulation of penetration of 6 mm of tool into blank.

Experimental trial after full penetration of 13 mm of tool into blank.



Simulation of full penetration of 13 mm of tool into blank.

Figure 4 Experiments and simulation.

In both cases ISO quality levels of 11 were recorded for pitch (F) and quality of 12 for tooth involute shape (f_α).

These results show that we are far from the quality level of 7 which is required if we wish to omit milling sequences after rolling. It might be possible to reach such quality levels but a significant amount of development work will be required to go from the present quality level of 11-12 to 7. Probably several innovative steps will be necessary to reach those required levels.

Figure 5 shows one of the gear wheels rolled at Fraunhofer IWU. Note the rabbit ears openings and the axial spreading of material. Figure 6 shows an etched cross section from the flank area. As can be seen, the surface area up to a depth of 0.5 mm is heavily cold worked. The surface of the flank is smooth.

Figure 5 Gear rolled gear wheel.

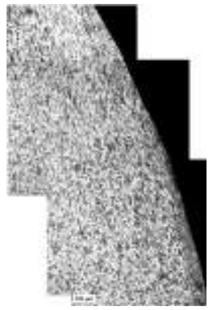


Figure 6 Etched cross section of flank area.

Contribution to FFI goals: No chips, less material needed, higher strength – reduced weight and/or higher quality, faster process – higher productivity.

5.2. WP3 Machining high loaded gears of clean steels

The torque load of heavy vehicle transmissions has increased by about three times in the last 20-30 years. This has been obtained with retained weight and room requirements of the transmission parts, by reduced tolerances, advanced heat treatments, new design solutions, among others. Today these solutions in materials engineering, production processes and new designs are extremely optimized. Further improvements are possible. The steels used in transmissions are micro alloyed and typically designed for carburizing, often referred to as "carburizing steels". A carburized gear is made up of about 1 mm case hardened to about 60 HRC and a core. The core has also a martensitic structure, though with the original carbon content resulting in a core of relatively high toughness. Clean steels have come up as a possibility to improve the root fatigue strength of gears. Rotating beam fatigue tests have shown a 20-40% improved fatigue strength. The entire manufacturing process is vital for the fatigue strength. Important aspects are the carburizing process itself, formation of subsurface oxide layers, the subsequent grinding or honing and the use of shot peening of the gear root.

The current tests aimed at evaluating the two candidates of high performance steels in Table 1 for heavy vehicle gears.

Steel producer	Denomination	Steel characteristics
Ovako	157C	Carburizing steel, S=40 ppm
Uddeholm	Orvar Supreme	Hot work tool steel, S=4 ppm

Table 1

Two demonstrators were used as references and as possible gear parts to introduce these clean steels, the 2nd gear of a Scania gear box and a planet gear of a Volvo gear box, see Figure 7. Both components are mass produced for current gear box models at their respective company. Drawings, specifications and machining process were made available from the industrial partners. The steels of the demonstrator components were of typical cleanliness, 0.02-0.04% S.

Figure 7 The 2nd gear of Scania and the planet gear of Volvo.

Their microstructures as obtained by light optical microscopy are given in Figure 8.

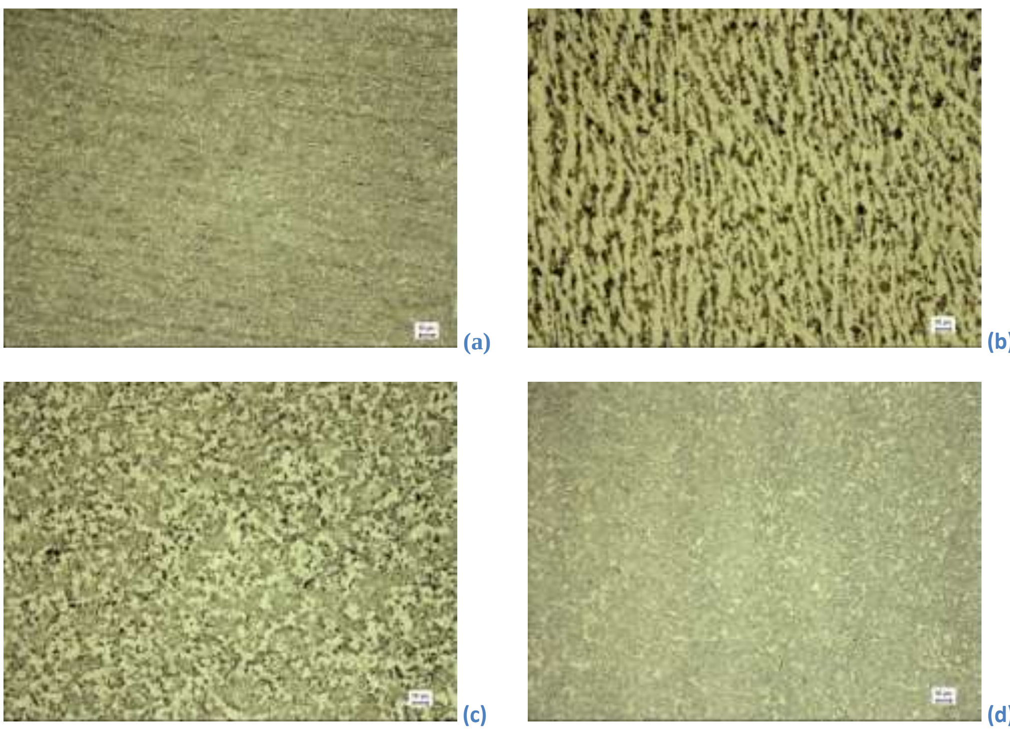


Figure 8 Representative microstructure of parts and materials used in cutting tests. (a) The planet gear of Volvo, (b) the 2nd gear of Scania, (c) used bar of Ovako 157C and (d) used bar of Uddeholm Orvar Supreme.

Tool life in rough turning is given in Figure 9. The planet gear of Volvo displayed a tool life about 30% better than that of the 2nd gear of Scania. The reason probably lies primarily in the different microstructures of the two materials. The bars of Ovako 157C displayed roughly the same tool life as the 2nd ring. The Uddeholm displayed significantly shorter tool life than the others. This was attributed to premature notch wear in those tests. The difference remained also at 300 m/min.

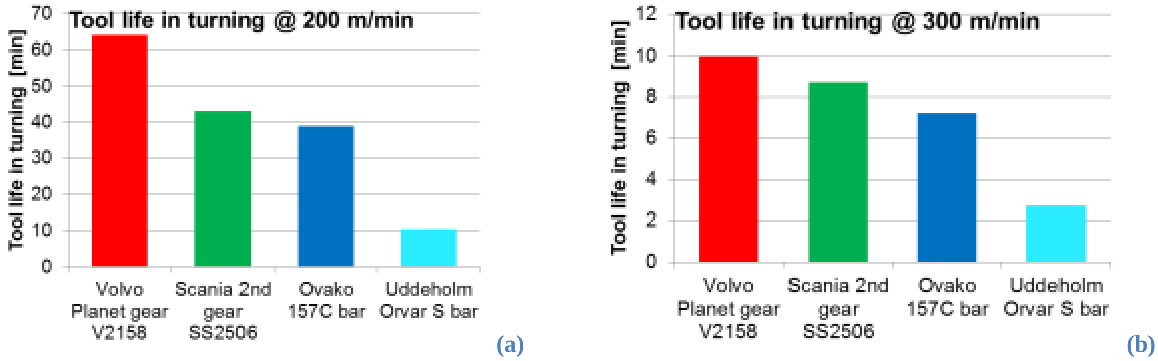


Figure 9 Tool life of the tested materials and geometries of the project at (a) 200 m/min and (b) 300 m/min.

A dedicated cutting test was designed to evaluate the abrasive constituents of the gear steels in order to clarify their machinability behavior. Abrasion of coatings of cutting tools is one of the most important wear types in both turning and in e.g. gear hobbing. One set of cutting data was defined. Face turning was utilized on both gear blanks and steel bars as test pieces. To exemplify the test procedure, cutting edge a) was subjected to 12 cuts, edge b) to 36, edge c) to 72 and edge d) to 144 cuts. This corresponded to the engagement times as given in Figure 10. Note that the four tested materials were subjected to the same chip cut length. Hence, the actual number of cuts was modified given by the outer and inner diameter of the cut of each test material. The results are given in Figure 11.

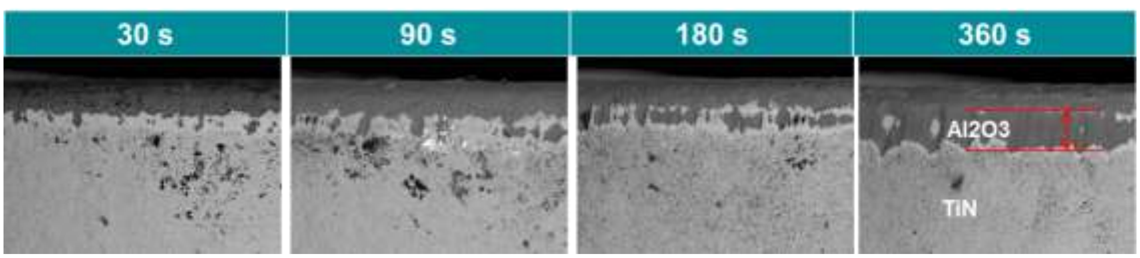


Figure 10 Schematic of the abrasion test and evaluation.

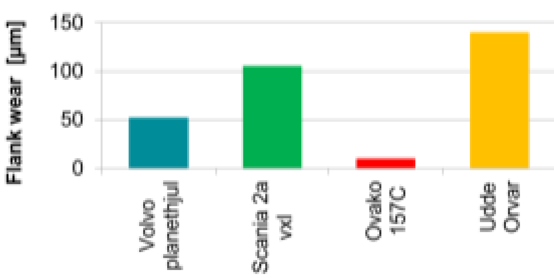


Figure 11 Bar chart of abrasion test results.

A designed machining test was developed to mimic the cutting conditions of conventional gear hobbing using PVD HSS hobs. A face milling concept was used with commercial circular cutting tools, see Figure 12. The resemblance to gear cutting is based on the following facts:

- Cutting inserts made of PVD-coated HSS. The cutting angles were modified so that they resemble those of actual solid hobs.
- The circular insert geometry mimics the variable chip thickness typical of gear cutting.

A cutting test was developed so that the chip cut volume would represent roughly one root metre of a typical gear. A stair-case test sequence was undertaken to find the cutting speed transition from go or no-go of this criterion of chip removal. The results are given in Figure 13.

Figure 12 The machining test designed to mimic the conditions of conventional gear hobbing.

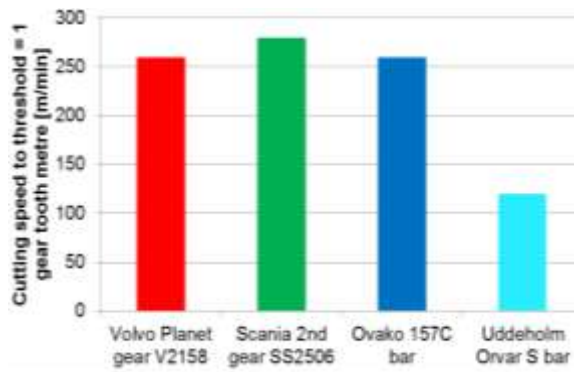
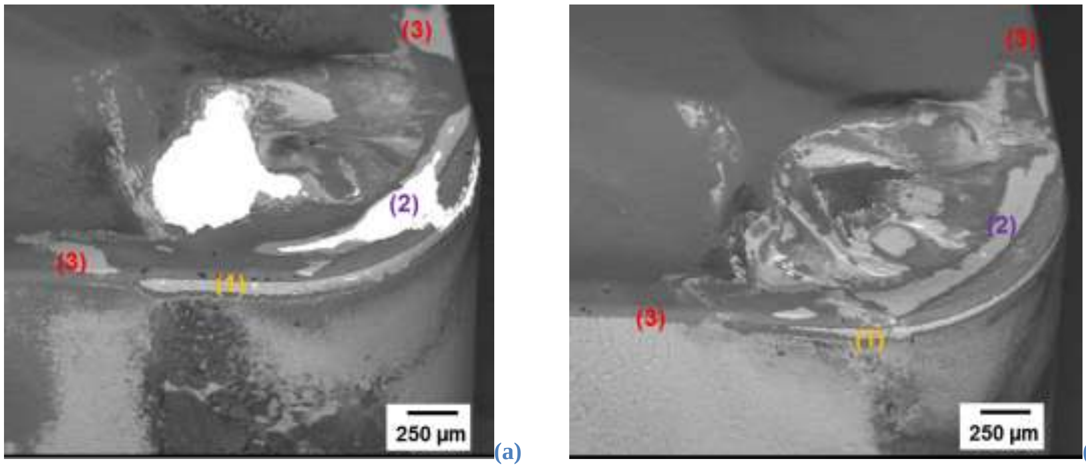


Figure 13 Bar chart of transition speed to meet the criterion of go and no-go of removed chip volume that corresponds to one gear root meter.

Field tests were undertaken in the introduction of an extremely clean steel with mechanical properties that are more isotropic as compared to conventional steel qualities. The denomination is Ovako 158Q. The tests were made with a planet gear of about 85 mm diameter. The reference steel was the same as being used at Scania, denominated SS2506. Its microstructure was obtained through controlled cooling. That of the Ovako 158Q was a typical as-delivered condition from the steel manufacturing. Their corresponding hardness was 162 HB (SS2506) and 192 HB (158Q). The most straightforward comparison of machining was sequences of 404 gears in rough turning. A Coromant CNMG120408 PM GC4325 cutting tool was utilized. The cutting speed vc=260 m/min, depth of cut ap=1-3 mm and feed f=0.3 mm.

Figure 14 shows cutting edges from the tests. (a) is from the Scania SS2506 and (b) is from the Ovako 158Q tests. (1) designates the flank face wear. (2) shows the rake face wear. Note the exposed carbide substrate (white area) in the micrograph of Scania SS2506. (3) designates the depth of cut and the coating wear of the cutting edge that originates from a scale layer from the ring forging of the Scania SS2506 tests. Also note that this observation is not part of the comparison of the steel machinability, but more a wear associated to the ring forging process.



(a) (b)

Figure 14 Micrographs of the cutting inserts used in field tests at Swepart Transmission. 404 planet gears were rough turned with (a) Scania SS2506 steel and (b) Ovako 158Q steel. (SEM-BS of etched cutting inserts)

The following conclusions can be drawn from this work, added with some thoughts and guidelines:

1. The difference in machinability of clean carburizing steels as compared to conventional carburizing steels with a sulphur content of S=0.02-0.04 wt.% is minor. Microstructural aspects are probably more important than the sulphur content. This is based on tests in rough turning and an experimental test that mimics gear hobbing.

2. In case of the tool steel investigated alternate machining strategies may be required. Another tool grade in rough turning than the one tested would probably increase the performance significantly. Maybe more demanding is the probable need to introduce new tooling concepts in the gear hobbing process. The high speed steel substrate of conventional solid hobs becomes over tempered at the cutting edge by the higher temperature generated in the chip removal of the hot work tool steel. However, hobs made of coated cemented carbide are commercially available both with solid and indexable concepts.

3. The machinability of clean steels can be characterized as follows:
   - Somewhat more adhesive in the tool-chip contact. This may generate premature coating wear in case of frequent entrances and exits in the process, e.g. in facing. Note that this can be solved by a modified CNC coding of the entrance into the cut.
   - Somewhat more difficult chip breaking. Roughly the transition from bad to good chip breaking is f=0.05 higher with clean steels.
   - Somewhat more heat in the cutting zone with clean steels. This is observed as more plastic deformation of the cutting edges in test with a clean steel as compared to a reference steel, if tested at the same cutting speed.
   - The combination of the new generation of textured alumina CVD coatings of turning tool grades and clean steels with a minimum of abrasive oxides and a fine grained microstructure makes a tremendous potential in increased productivity.
   - The minimal abrasive wear constituents of these steels makes a high and robust tool life also with PVD coated solid hobs.

Thoughts and ideas in the possibilities with clean and high performance steels in gears:

1. It is recommended to investigate the introduction of ultra clean steel from tube product directly in gears. The change would enable a saving in lead time from the steel mill to the manufactured gear.

2. Significant improvements in productivity and production robustness can be obtained by modifying the relatively coarse microstructure of today's steels as-forged. In general a fine grained microstructure is better than a coarse microstructure for the tool life and robustness of the cutting tools.

3. Ca-treated steels have a strong potential in increased both robustness and productivity in gear production. This was not part of the SMART project but based on other research.

4. Within the project accelerated and representative cutting tests have been developed with the potential to compare the machinability characteristics of steels for gears. The tests can be performed on steel bars and on forgings. The following processes can be screened from a machinability aspect:
   - rough turning
   - gear hobbing, through a further developed test in face milling with a commercial milling concept with circular inserts made of PVD-coated high speed steel
   - hard part turning (as part of other research).

5. Two machining processes not addressed in this work can be highlighted as possible areas of difficulties with clean steels. They are drilling and broaching. More research is recommended in these areas to clarify possible difficulties.

6. The four steels of the project have been compared with the same tooling solutions. The important next step could be to develop practical solutions in the machining processes. Alternate tooling grades is a straightforward example of such a solution.

7. The investigated materials had their own geometry, bars (of different diameter) of the Ovako 157C and Uddeholm Orvar Supreme, A D=85 mm planet gear of Volvo and a D=145 mm second gear of Scania. The influence of geometry in the tests is likely. For a future research project it is recommended to use the same geometry of all four steels. Perhaps the planet gear geometry is the most easily obtained.

Dimensional tolerances, e.g. the outer diameter, of the forging, as well as possible remnants of scale layers are probably more important origins of premature tool fracture and production stops than the small reduction in machinability of a clean steel.

Contribution to FFI goals: Higher strength – reduced weight and/or higher quality.

5.3. WP4 Influence of hardenability on heat treatment distortions

Distortion is a major concern in production of gears and other powertrain components. Understanding and quantifying the factors influencing distortion has for long been a concern in the field of heat treatment. Prediction of these factors enables both significant cost savings and improved product quality. Despite all the efforts, predicting distortion after case hardening is still very challenging. The ultimate objective is to determine the relation between cause and effect throughout the entire process chain: steelmaking, casting, rolling, forging, machining and hardening. Hardening is usually the primary trigger for distortion, although the distortion potential is built-up throughout the whole production chain. Distortion has attracted a lot of attention lately, in particular by the German initiative Collaborative Research Center "Distortion Engineering". The name implies the new methodical approach of treating distortion as a system attribute of the entire process chain. This may seem obvious to some; even so it is very important to make this recognition. In other words: It is necessary to have the "system attribute"-mindset when performing research on distortion engineering.

In this project the attention was directed to the effect of hardenability on distortion. Hardenability refers to the ability of steel to form martensite at a certain cooling rate. It should not be confused with hardness. The hardness obtained on hardening is primarily dependent on the steel’s carbon content provided that the cooling rate during hardening has been higher than the critical rate, i.e. that transformation to martensite takes place without any formation of pearlite or bainite or other, softer structural components. Hardenability should be treated as a parameter. It is defined as the "susceptibility to hardening by rapid cooling" or as "the property, in ferrous alloys, that determines the depth and distribution of hardness produced by quenching". In general, an increase in alloying content permits a decrease in cooling rate, i.e. increases the hardenability. Hardenability can be experimentally determined or calculated. Numerous studies have found that hardenability has a strong influence on distortion after case hardening. The effect is significant and rather complex, since hardenability is a property with several dependencies. The vast majority of hardenability calculation methods are assessed from hardness testing of commercial steel grades. There is also the opinion about replacing actual hardness testing with calculations, since scattering from the testing can be handled more efficiently. According to international standards it is also possible, on the basis of agreement between customer and steel supplier, to replace testing with calculation on condition that an accepted calculation model is employed. Most steel suppliers have developed formulae for calculation of hardenability, which are based on regression analysis from a large number of hardness test carried out on their material. In addition, there are several regression models for calculation of hardenability available. These generic models are usually not fit for precise hardenability calculations on a given heat of steel. Rather they should be used for comparing hardenability among different steel grades. A well specified hardenability interval is an important criterion for the component manufacturer to establish a sound heat treatment process and minimize distortion. Hence, correct hardenability information on a given heat is necessary for efficient distortion engineering.

To study the effect of hardenability on distortion this project recognized the current state-of-the-art for distortion engineering. It is known that carriers of distortion are found throughout the whole production chain and in that sense can be considered generic for any product. Nevertheless, when conducting distortion engineering it is necessary to be more component-specific due to the high level of complexity of the subject. In this project we have made an effort to research the more generic effects of hardenability on distortion by a substantial literature survey and by heat treatment experiments on simple geometries. In addition, we have attempted to isolate the effect of hardenability on distortion on a number of components in production in Swedish industry.

For the heat treatment experiments on simple geometries we used steel grade 16NiCrS4 (SS2511), which is a carburizing case-hardening steel. Three different heats, with different chemical composition, of this steel grade were supplied as tubes with an outer diameter of 71.5 mm and a wall-thickness of 17 mm. From the tubes two simple geometries were machined: (1) a ring with 70 mm outer diameter, wall-thickness of 16 mm and height 19 mm. (2) a modified Navy C-ring as seen from Figure 15. The alloying content and hardenability of the steel heats are presented in Table 2 and Figure 16, respectively. The calculated value provided by the steel producers indicated that hardenability of A < B < C.

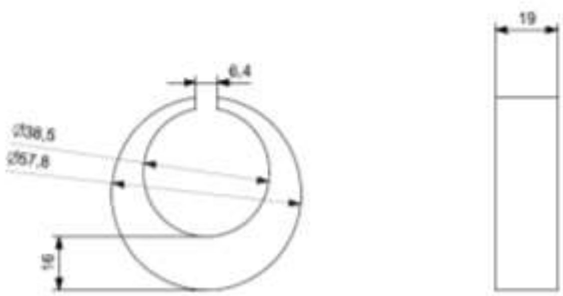


Figure 15 Shape of C-ring used for heat treatment experiments, measurments are given in [mm].

Steel heat	C	Si	Mn	P	S	Cr	Ni	Mo	Cu	Al	Fe
Heat A	0,20	0,07	1,00	0,012	0,041	1,01	1,03	0,13	0,17	230 ppm	Bal.
Heat B	0,20	0,07	1,03	0,016	0,041	1,04	1,05	0,17	0,17	190 ppm	Bal.
Heat C	0,20	0,07	1,02	0,008	0,041	1,03	1,39	0,16	0,18	250 ppm	Bal.

Table 2 Chemical composition of 16NiCrS4 heats.

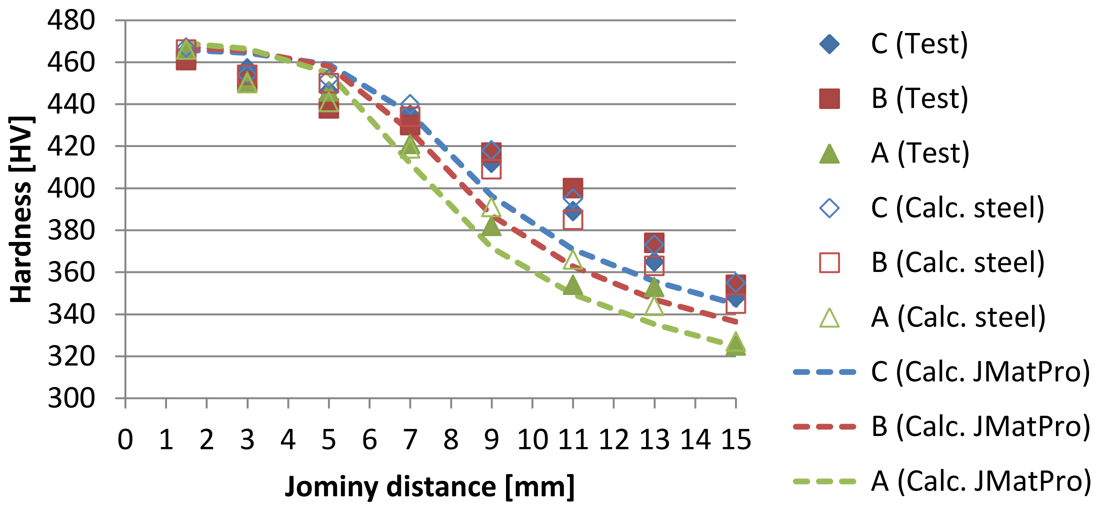


Figure 16 Hardenability of the three heats of 16NiCrS4 used in this project. Heats are named A, B and C. Hardenability is given as: (Test): Jominy test according to ISO 642; (Calc. steel): Calculated with model from steel supplier; (Calc. JMatPro): Calculated with generic model built in to JMatPro software (version 8).

In total 30 C-rings and 60 rings were heat treated and analyzed for distortion, of which one-third from steel heats A, B and C respectively. A 3D-scanner was used for distortion analysis of C-rings and a coordinate measuring machine (CMM) was used for the rings. The C-rings and rings were first machined and then annealed for stress relief. Then their geometry was measured before and after heat treatment to determine the shape change after hardening, i.e. distortion. Heat treatments were done as follows:

C-rings:

- (Stress relief annealing - 600 °C, 5 h)
- Heating – austenitization at 850 °C in vacuum for 1 hour, no carburization.
- Quenching – two different batches:
  - 15 C-rings in oil at 45 °C, Petrofer VACUQUENCH 305.
  - 15 C-rings in nitrogen gas at 9 bar.

Rings:

- (Stress relief annealing – 600 °C, 5 h)
- Heating – austenitization at 850 °C for 1 hour, no carburization.
- Quenching – two different batches:
  - 30 rings in oil at 50 °C, Petrofer ISORAPID 229 FQ.
  - 30 rings in salt at 180 °C.

The hardness was analysed for the different test pieces and heat treatments. With respect to distortion cooling should not be faster than required to achieve requested hardness. Here we used four different quenchants, which resulted in different hardness of the simple geometries. As can be seen from Table 3, gas quenching in nitrogen at 9 bars cannot be used to harden these C-rings made from 16NiCrS4. On the other hand, the VACUQUENCH 305 oil had sufficient cooling capacity to achieve a hardness of about

40 HRC. A faster quenching oil, ISORAPID 229FQ, used for the rings resulted in an even higher hardness, close to the ultimate hardness of this steel grade in non-carburized condition. When instead salt was used the difference in hardness among the three heats was large. It is clear that the present steel grade and geometry is not well matched with the cooling capacity of this particular salt.

The C-ring shape, Navy C-ring, has been used previously to analyze distortion. Apart from regular transmission geometries, the C-ring has an open geometry that becomes more sensitive to distortion. Here we measured the distortion of the 6.4 mm gap, as seen from Figure 15. The gap width was analyzed from the 3D-scanner results and it was concluded that it widened on hardening. The distortion was 5 hundreds of a mm for all the nitrogen quenched C-rings, hence no effect of hardenability, which also correlated with the hardness result. For the oil quenched C-rings the distortion was larger, 30-50 hundreds, with Heats A and B at the lower limit and heat C at the higher limit. Although, the effect of hardenability is recognized the statistical basis is rather small.

The ring distortion was measured using a CMM. Here we focus on the change in ring height and radial distortion, i.e. change in inner and outer diameter. The relative changes in height were proportional to the hardenability; 1, 1.5 and 2 hundreds for heats A, B and C, respectively. The radial distortion was measured at three different heights. As seen from Figure 17, the inner and outer surfaces becomes convex and concave, respectively, after quenching. Regarding the diameters, they shrink for heats B and C, but grow for heat A. Hence; a ring of lower hardenability becomes flatter and wider while a ring of higher hardenability becomes thicker and narrower. In both cases the inner surface becomes convex, while the outer becomes somewhat concave.

	C-rings (10 rings/heat)		**Rings (20 rings/heat)**	
Steel heat	VACUQENCH 305	Nitrogen gas	ISORAPID 229FQ	SALT
Heat A	41.3±2.2	28.0±2.7	45.3±0.4	35.5±0.7
Heat B	39.7±1.7	28.0±1.6	44.9±0.5	40.1±1.2
Heat C	39.9±1.3	28.3±0.9	45.0±0.6	42.1±0.7

Table 3 Measured hardness [HRC] of heat treated C-rings and rings. Hardness is presented as the mean over all specimens from a batch, with three hardness tests per specimen. Precision is given as one standard deviation.

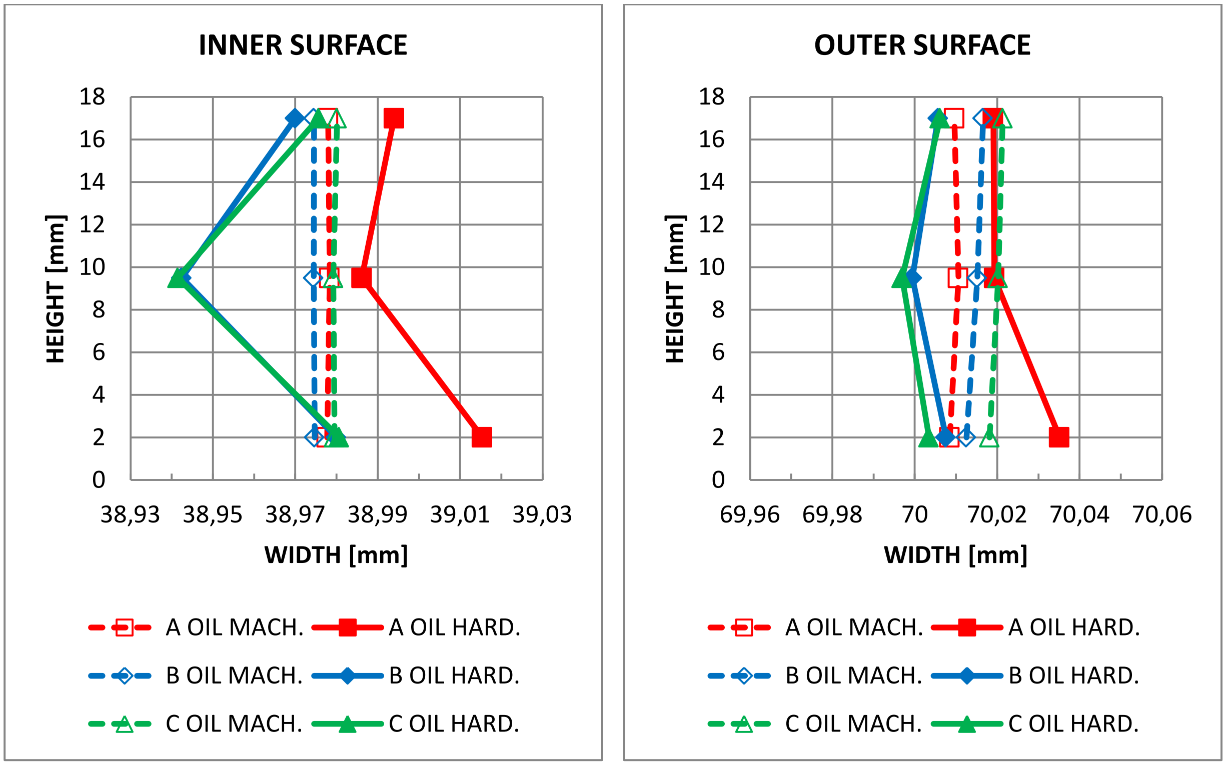


Figure 17 Radial distortion of oil quenched rings. The inner and outer surfaces becomes convex and concave, respectively. The inner diameter shrinks for heats B and C, but grows for heat A.

Apart from studying distortion of simple geometries, we studied three types of components currently in production: (1) crown wheels, (2) pinions and (3) annular gears. The purpose was to isolate the effect of hardenability on distortion. The data set contained:

- 98 crown wheels from 5 different steel heats
- 288 pinions from 3 different steel heats
- 10 annular gears from 2 different steel heats.

A summary of some general comments on distortions:

- Upon hardening martensite is formed, with a greater volume than the parent phase. This results in distortion, which is to some extent predictable and thus can be compensated for in soft machining.
- Unwanted, non systematic, changes in shape that appears after heat treatment is complex and can be caused by many factors.
- All steps in manufacturing the steel and manufacturing of components are carriers of distortion potential showing as distortions after heat treatment.

The results from the distortion study on simple geometries and components in production can be summarized as follows:

- The effect of hardenability on distortion is significant. This project has shown that distortion of simple geometries as well as industrial components is effected by hardenability, i.e. alloying content.
  - It is important to be consistent in method how to calculate the hardenability and to follow-up variations in hardenability for different heats.
  - Also alloying elements that are not covered in hardenability models influences on distortions, e.g, (Al, Ti, Al/N).
- Hardenability dependent geometrical compensation in soft machining seems feasible for reducing the detrimental effects of distortion. The compensation has to be worked out from controlled production trials and most probably independently for every steel supplier.

- Hardenability data provided by the steel producers seems more reliable when compared to calculations done by common methods.

There is a good potential to systematically study distortions through production monitoring. Identify relevant factors and keep as many of them as possible constant and only study variations in hardenability and chemical composistion. Multivariate data analysis is a useful tool.

Contribution to FFI goals: Higher quality.

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 previous gear projects in MERA and FFI. 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 is planned to be maintained in the future.

A concluding activity in the project was a roadshow to Södertälje (Scania host), Liatorp (Swepart Transmission host) and Köping (Volvo host) to report industrially applicable results on the spot. This initiative was highly appreciated and drew large audiences.

The project results are also reported in a wiki: http://130.237.56.41/mediawiki/index.php/FFI_Sustainable_manufacturing_of_future_transmission_parts_%E2%80%93_SMART.

6.2. Publications

Alireza Khodaee and Arne Melander, Finite Element Simulation as a Tool to Evaluate Gear Quality after Gear Rolling, http://www.scientific.net/KEM.554-557.300, ESAFORM 2013- Aveiro, Portugal (2013) 300-306

Alireza Khodaee and Arne Melander, Finite Element Analysis on the Friction Effects in the Gear Rolling Process, Stockholm, Sweden NEWTECH (2013) Vol 2, 93-102

Alireza Khodaee and Arne Melander, Study of the Effect of the Reversal Cycles in the Gear Rolling Process by Using Finite Element Simulations, http://www.scientific.net/KEM.611-612.134, ESAFORM 2014, May (2014)- Finland 134-141

Alireza Khodaee and Arne Melander, Finite Element Study of Rolling Loads in Gear Rolling of High Gear Wheels, , http://www.scientific.net/KEM.622-623.986, METAL FORMING- Sept (2014)- Italy 986-992

Alireza Khodaee, Sven Haglund and Arne Melander, Case study for development of gear rolling process to use in heavy vehicle transmission production with Finite Element Method, possibilities and limitations (to be published)

Alireza Khodaee and Arne Melander, Modifications of blank geometry to gain better product by gear rolling process with Finite Element Method (to be published)

A. Stormvinter, H. Kristoffersen, A. Olofsson, K. Biwersi, and S. Haglund, Effect of Hardenability and Press Quenching on Distortion of Crown Wheels, 5th International Conference on Thermal Process Modeling and Computer Simulation, 2014, pp. 149-155.

Project summary published in Värmebehandlingsforum nr 3-2012

20th Congress IFHTSE, 23-25 October 2012

Presentations at The Swedish Heat Treatment Centre member meetings 2013, 2014 and 2015

Presentations at Cluster conference in Katrineholm 2014, 2015

Summary of final results in Värmebehandlingsforum June 2015 (planned)

Presentation at Heat Treatment conference, Aktuellt om material och värmebehandlingsteknik, Västerås, 22-23 sept 2015: Härdbarhetens inverkan på formförändringar, Hans Kristoffersen, Swerea IVF (planned)

Presentation at 5th Int Conf on Distortion Engineering, 23 -25 September 2015, Bremen, Germany: Effects of Hardenability and Quenching on Distortion of Steel Components, Albin Stormvinter, Swerea IVF (planned)

7. Conclusions and future research

In conclusion, it can be stated that gear wheels of size typical to truck gear boxes cannot be manufactured by gear rolling with sufficient accuracy at the present moment. The shape deviations on gear flanks are so large that additional milling will be needed after rolling. Under those conditions the introduction of rolling will be too complex and expensive in a production line. In all other respects the gear rolled wheels showed good properties. So if in the future developments can be made in the rolling process to minimize shape inaccuracies the method can become applicable and the advantages in material consumption and fatigue properties can be utilized also for truck applications. But we are not at that point now.

It is recommended to investigate the introduction of ultra clean steel from tube product directly in gears. The change would enable a saving in lead time from the steel mill to the manufactured gear. Significant improvements in productivity and production robustness can be obtained by modifying the relatively coarse microstructure of today's steels as-forged. In general a fine grained microstructure is better than a coarse microstructure for the tool life and robustness of the cutting tools. Ca-treated steels have a strong potential in increased both robustness and productivity in gear production. This was not part of the SMART project but based on other research. Within the project accelerated and representative cutting tests have been developed with the potential to compare the machinability characteristics of steels for gears. The tests can be performed on steel bars and on forgings. The following processes can be screened from a machinability aspect: a) rough turning, b) gear hobbing, through a further developed test in face milling with a commercial milling concept with circular inserts made of PVD-coated high speed steel and c) hard part turning (as part of other research). Two machining processes not addressed in this work can be highlighted as possible areas of difficulties with clean steels. They are drilling and broaching. More research is recommended in these areas to clarify possible difficulties. The four steels of the project have been compared with the same tooling solutions. The important next step could be to develop practical solutions in the machining processes. Alternate tooling grades is a straightforward example of such a solution. The investigated materials had their own geometry, bars (of different diameter) of the Ovako 157C and Uddeholm Orvar Supreme, A D=85 mm planet gear of Volvo and a D=145 mm second gear of Scania. The influence of geometry in the tests is likely. For a future research project it is recommended to use the same geometry of all four steels. Perhaps the planet gear geometry is the most easily obtained.

The effect of hardenability on distortion is significant. This project has shown that distortion of simple geometries as well as industrial components is affected by hardenability, i.e. alloying content. It is important to be consistent in method how to calculate the hardenability and to follow-up variations in hardenability for different heats. Also alloying elements that are not covered in hardenability models influences on distortions, e.g, (Al, Ti, Al/N). Hardenability dependent geometrical compensation in soft machining seems feasible for reducing the detrimental effects of distortion. The compensation has to be worked out from controlled production trials and most probably independently for every steel supplier. Hardenability data provided by the steel producers seems more reliable when compared to calculations done by common methods. There is a good potential to systematically study distortions through production monitoring. Identify relevant factors and keep as many of them as possible constant and only study variations in hardenability and chemical composition. Multivariate data analysis is a useful tool.

8. Participating parties and contact person

The project partners are listed below.
Academic: KTH Royal Institute of Technology, Swerea KIMAB AB and Swerea iVF AB
Automotive: Scania and Volvo
Automotive subcontractors (Fordonskomponentgruppen, FKG): Bodycote Värmebehandling, GKN Drivline Köping, Leax, Ovako Hofors, SwePart Transmission, Uddeholm
Other companies: Oerlikon Balzers, Sandvik Tooling

Project leader: Thomas Lundholm, KTH Royal Institute of Technology, tlun@kth.se, +4687906381