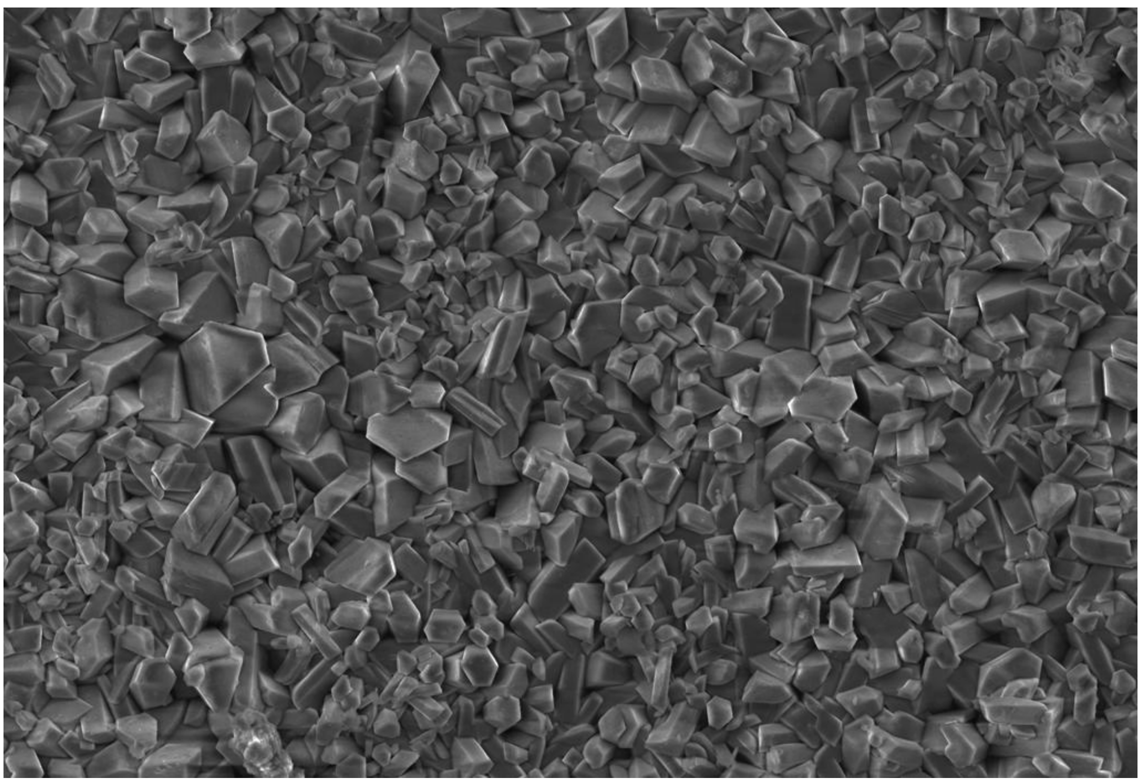
Manganese phosphating for increased contact fatigue



Project within FFI-Fordonsutveckling

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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.**

For more information: www.vinnova.se/ffi

1. Executive summary

The FFI-project “Manganese phosphating for increased contact fatigue” was executed in cooperation between Scania, Swerea IVF AB and Swerea KIMAB AB. The main objective of the project was to increase the knowledge of the manganese phosphating process and its influence on the contact fatigue strength. This included the development of methods to evaluate different process parameters influencing the creation of the manganese phosphating coatings. Also methods to evaluate the contact fatigue performance for hypoid gears (axle) and spur and helical gears (gearbox) was evaluated and used within the project.

The project was conducted in close cooperation between the participant organizations. At Swerea IVF AB the team consisted of different researchers during the progress of the project. Carolina Pettersson (PhD) was the project responsible when the project was finalized. Swerea IVF AB has long experience of working with surface treatments, including phosphating, and has a pilot production line which is suitable for process studies. This knowledge was applied to the manganese phosphating process. At Swerea KIMAB AB Sven Haglund (PhD) was the project responsible. The group at Swerea KIMAB AB has studied contact fatigue for a long period of time. The rig used is suitable for gear like conditions with the possibility to vary the slip. The method uses two rollers in contact and a damage length is evaluated after a certain number of revolutions. The roller testing generated results for different steels and surface treatments but was not able to generate results for the manganese phosphated rollers.

To be able to evaluate the manganese phosphate coatings; fatigue testing was bought by a third party institute in Germany (Laboratory for Machine Tools and Production Engineering (WZL) of RWTH Aachen University). The testing was performed in a FZG rig (with gears instead of rollers). This testing was very successful and contributed with valuable contact fatigue strength data.

The project was successful in providing valuable input to the gearbox and axle development. The optimization of the manganese phosphating layer was successful and the project showed the advantages and disadvantages of the manganese phosphating depending on which component that is used. It has also led to improved testing and new methods for evaluation of gear performance. The research performed within the project showed that the manganese phosphating is beneficial for gearbox applications. Still it is important to continue the evaluation and verification especially in combination with different lubricants. This project will continue as an internal project and the cooperation with Swerea IVF AB and Swerea KIMAB AB will continue.

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2. Background

The purpose with this report is to summarise some of the most important results in the FFI-project “Manganese phosphating for increased contact fatigue”. The project was executed in cooperation between Scania, Swerea IVF AB and Swerea KIMAB AB.

The demands on vehicles are constantly increasing. There are demands for increased durability, longer service intervals, stronger power train and a need for lighter and smaller constructions. The limiting factor in the gear box today is the gears which are subjected to both contact- and gear root bending fatigue. This project addressed the contact fatigue strength. Also the scuffing (seizure) performance was evaluated to some extent.

Contact fatigue appears at cyclic loading with high contact pressure and might lead to the formation of pits. This is caused by surface defects or by external defects, such as debris in the oil. Hence it is of great importance to reduce local metal to metal contact. There are many strategies to reduce this and lubrication is of vital importance. One method can be to use manganese phosphating.

Pawelec et al[1] studied the effect of different oils on contact fatigue and found that for mineral oil the contact fatigue resistance increased with increasing viscosity. However, for synthetic oils no significant differences were found. If it would be possible to decrease the viscosity of the oil without causing pitting damages, fuel consumption would be reduced. Unfortunately there are no studies available on how different oils will affect contact fatigue of manganese phosphated surfaces.

During manganese phosphating crystals of manganese phosphate grow on the surface which effectively prevents metal to metal contact during running in. The coating is believed to wear off rather quickly. The size of the crystals varies greatly with process conditions and the process also involves pickling of the surface, which produces pits. The effect of pickling pits and crystal size on the contact fatigue life is unknown and needs to be clarified. Very few works have been published on the effects of manganese phosphating. Chen et.al[2] showed that manganese phosphating increase fatigue life significantly, by up to four times. Chen also claims that the pickling pits are favourable since they could act as oil-reservoirs.

Contact fatigue of gears

There are essentially two mechanisms active in contact fatigue of gears, micropitting and pitting. Micropitting is on a much smaller scale, ~10µm see figure 1a, and is often considered harmless. Micropitting is initiated at the surface and when a certain crack length is reached a small fragment spalls off. This leads to a grey staining of the surface. Micropitting damages may progress further and further and thus change the geometry of the gear and / or initiate pitting.

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[1] Pawelec, Z; Dasiewicz, J; Piekoszewski, W; Tuszynski, W “ROLLING CONTACT FATIGUE LIFE FOR ELEMENTS LUBRICATED WITH MINERAL AND SYNTHETIC BASE OILS” Tribologia (Poland). Vol. 35, no. 3, pp. 351-362. 2004

[2] Chen Y., Yamamoto A., Omori K., “Improvement of Contact Fatigue Strength of Gears by Tooth surface Modification Processing”, 12th IFToMM World Congress, Besancon (France) June 18-21 (2007)

Micropitting occurs under elastohydrodynamic lubrication (EHL) where oil film thickness is of the same order as the combined surface roughness[3]. Micropitting is strongly influenced by friction forces i.e. the slip between the mating surfaces, which moves the maximum stressed zone towards the surface. This means that micropitting occurs where the sliding is high, i.e. not in the centre of the gear where pure rolling is present, see figure 1b. Figure 2a shows the typical appearance of a micropitted surface.

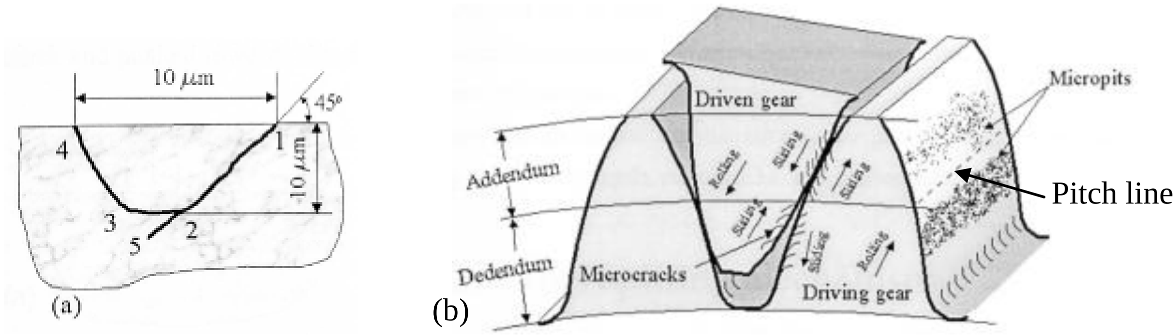


Figure 1. a) Development of micropitting. b) Micropitting and direction of micropitting cracks on gear surfaces. The orientation of the cracks changes at the pitch line due to the different sliding directions[4].

Pitting is on a much larger scale where chunks several millimetre in size may spall off, see figure 2b. These damages are formed in a similar way as micropitting but are initiated either at the surface or at an inclusion below the surface. This type of pitting is considered catastrophic and the gear must be replaced. *The focus of the project was therefore pitting damages.*

Since micropitting leads to local removal of material; stress might increase at the point where micropitting ends. This is where pitting damages are often initiated[5], i.e. closer to the pitch line. Figure 2b shows the initiation site of a pitting damage in a gear. It seems like micropitting fatigue cracks have initiated the pitting damage.

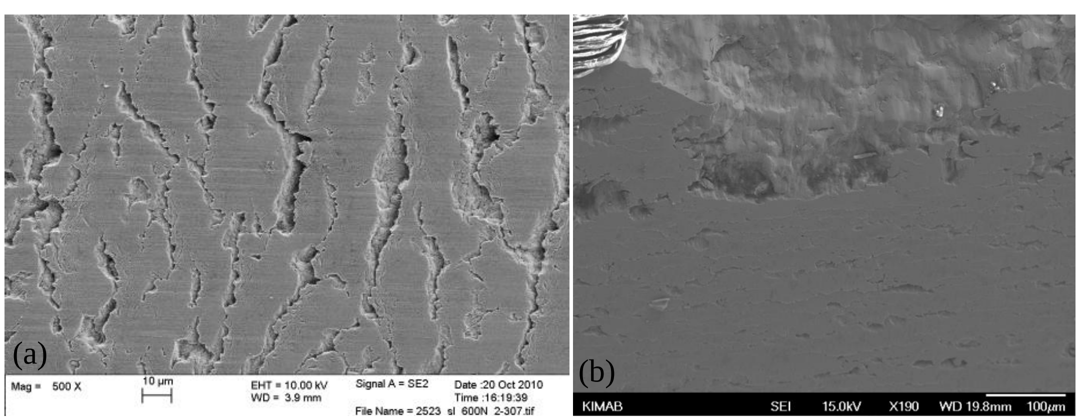


Figure 2. a) Typical appearance of micropitting. b) Initiation of a pitting damage.

[3] "Wind Turbine Micropitting Workshop: A Recap", Technical reort NREL/TP-500-46572 February 2010

[4] Oila A., "Micropitting and Related Phenomena in Gas Carburised Gears", Phd thesis University of Newcastle upon Tyne (2003)

[5] Drago R.J., Cunningham R.J., Cymbala S., " The Anatomy of a Micropitting-Induced Tooth Fracture Failure – Its Causation, Initiation, Progression and Prevention", Gera Technology, June (2010), pp 63-69

3. Objective

The main objective of the project was to increase the knowledge of the manganese phosphating process and its influence on the contact fatigue strength. This included the development of methods to evaluate coatings created with different process parameters and to evaluate the contact fatigue strength for gears.

Further, the project was expected to generate knowledge on how to optimise the manganese phosphate coating for increased contact fatigue strength. This will give a possibility to reduce the fuel consumption by reducing the viscosity of the oil without risking the overall endurance of the gears. Another important area is the hybridisation of trucks and busses. This requires a change in oil technology which will cause reduced protection against scuffing (seizure) and contact fatigue.

In the longer term, the project was expected to generate knowledge that can be used to determine whether other coatings or surface treatments can be used to protect the gear surfaces but with reduced usage of chemicals.

4. Project realization

At Scania the department Materials Technology for Axle and Transmission was responsible for executing the project in close cooperation with Swerea KIMAB AB and Swerea IVF AB.

At Swerea IVF AB the team consisted of different researchers during the progress of the project. Carolina Pettersson (PhD) was the project responsible when the project was finalized. Swerea IVF AB has long experience of working with surface treatment, including phosphating, and has a pilot production line which is suitable for process studies. This knowledge was applied to the manganese phosphating process. Swerea IVF AB used beakers and the pilot line to study, evaluate and optimize the manganese phosphating process. Swerea IVF AB also developed methods to evaluate and classify the manganese phosphated coatings. Multivariable analyses were performed on the process parameters to find the primary factors influencing the coatings. In the final stage the pilot line was used to manganese phosphate gears for contact fatigue testing.

At Swerea KIMAB AB Sven Haglund (PhD) was the project responsible. Swerea KIMAB AB has studied contact fatigue for a long period of time and different types of surface hardenings have been studied extensively[6]. This knowledge was applied to the project. The test rig uses two rollers in contact with a variable slip (suitable for gear testing). Swerea KIMAB AB developed a method to measure and evaluates contact fatigue damages from the testing. The roller testing generated results for different steels and surface treatments but was not able to generate results for the manganese phosphated rollers. Unfortunately the test rig used was not suitable for the contact pressure that was needed to evaluate the contact fatigue strength of the manganese phosphating. Testing

[6] Meurling, F., Melander, A., Tidesten, M. and Westin, L., Influence of carbide andinclusion contents on the fatigue properties of high speed steels and tool steels, International Journal of Fatigue, Vol.23, Issue 3, pp 215-224 (2001)

was aborted prematurely and the funds from Vinnova were redistributed within the project. Still Swerea KIMAB AB provided important results to the project.
To be able to evaluate the manganese phosphate coatings; fatigue testing was bought by a third party institute in Germany (Laboratory for Machine Tools and Production Engineering (WZL) of RWTH Aachen University). The testing was performed in a FZG rig (with gears instead of rollers). This testing was very successful and contributed with valuable contact fatigue strength data.

Scania was responsible for supplying test material i.e. rollers with different steel grades and surface treatments. Scania provided process data from production and parameters used in the testing (calculated to resemble the gear contact in a Scania gearbox). In the project Scania performed several large scale fatigue tests to thoroughly investigate the manganese phosphating. Both spur and helical gears (gearbox) and hypoid gears (axle) were investigated. Two full scale axle fatigue test campaigns with evaluation of manganese phosphating coating compared to other surface treatments were carried out. For gearbox two major investigations were made. The scuffing performance was evaluated in full scale gearbox fatigue test and the contact fatigue strength was evaluated in a Scania back to back gear test rig (FZG type).

Due to the premature ending of the roller testing the comparison with different lubricants was not possible to start. This part is planned in coming projects.

The communication between Scania and the institutes was carried out with a series of telephone meetings and small seminars. In addition, a steering group with representatives from Scania followed and controlled the progress of the project.

5. Results and deliverables

5.1 Process study

The process study focused on two steps: the activation and the manganese phosphating (see figure 3). All other steps were kept constant during the experiments.

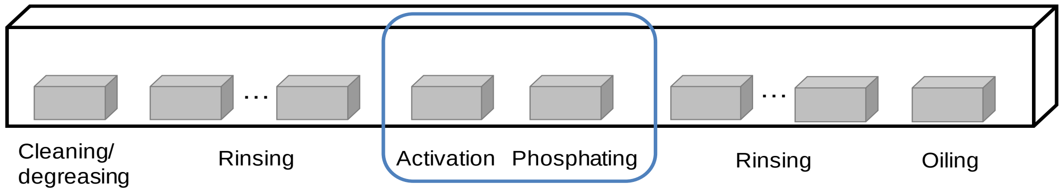


Figure 3. Common steps in the manganese phosphating process.

Beaker experiments were made in order to find the process parameters that have the largest effect of the formation of the coating. After that, pilot plant experiments were made with the final goal to produce well defined phosphate coatings on gears for pitting tests. The pilot plant for surface treatment at Swerea IVF AB is equipped with baths for spray or dip treatment. The line has an automatically operating carrier which can be programmed for required treatment times and pauses.

Method for evaluation and examination of coated surfaces

The crystal size and the general appearance, including coverage and possible defects was studied in SEM (Scanning Electron Microscope), see figure 4a. Cross sections mounted in bakelite were studied in light optical microscope, see figure 4b, and the pickling pits were counted. An image analysis macro was developed and used for measurements of coating thickness and surface roughness, see figure 5.

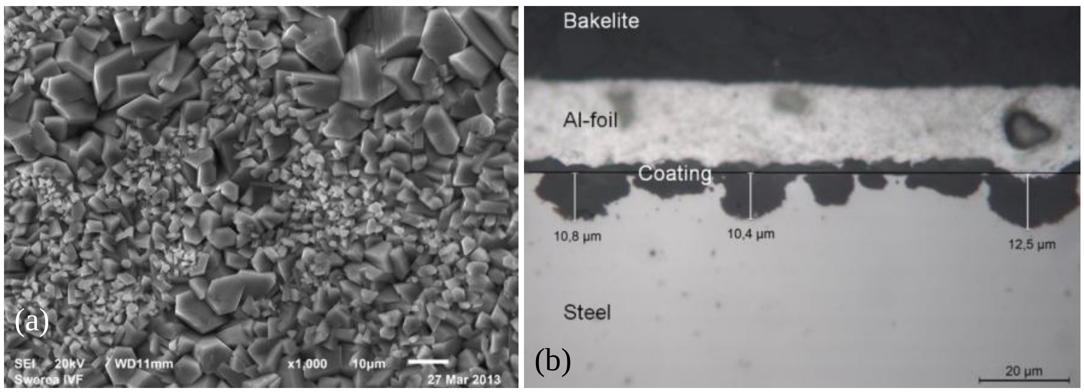


Figure 4. a) SEM image of a manganese phosphated sample showing 100 % coverage and varying crystal sizes (about 2-20 µm). b) Cross section of a manganese phosphated sample with pickling pits. The aluminium foil was placed before baking in bakelite in order to distinguish the coating from the bakelite.

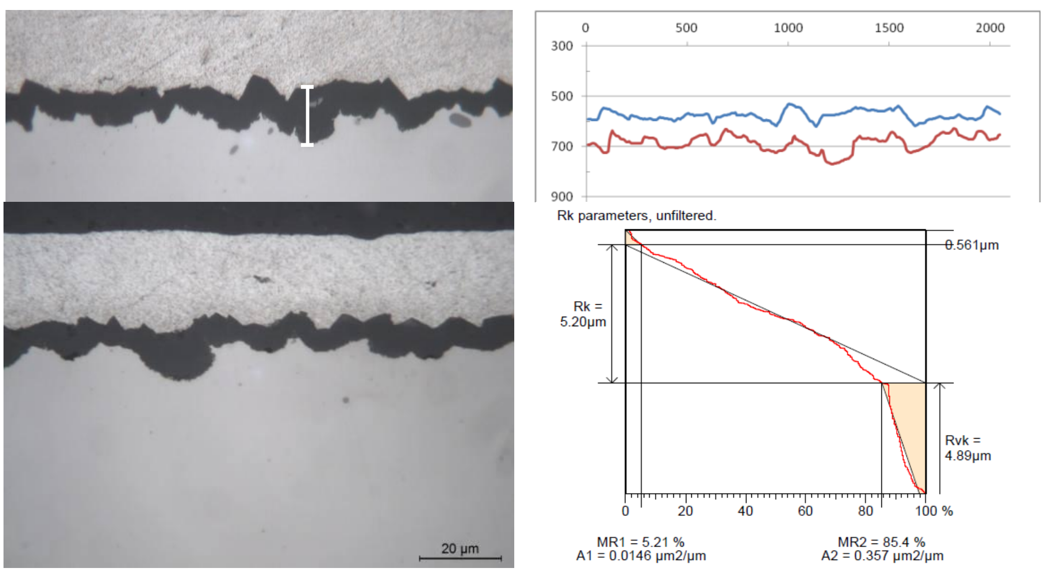


Figure 5. Cross sections and examples of results from the image analysis.

Beaker tests

The tests showed that increased activation salt A resulted in smaller more uniform sized crystals and also a decreased coating thickness. Increased concentration of the manganese phosphating (MnPh) chemical resulted in increased coating thickness and increased number and depth of pickling pits. Also the crystal size had a tendency to increase with increasing of the MnPh chemical, but no clear trend was visible. A temperature of 95 °C instead of 85 °C in the manganese phosphating bath did not lead to a better coating, rather the opposite.

A new way to classify the coatings was developed during analysis of the beaker scale experiments. The coatings were divided into classes from 1 to 5 (see figure 6), where class 1 describes a thin coating with small crystals and no pickling pits. Class 5 describes a thick coating with large crystals and heavy but even pickling. In between is the class 3 coating, which is a coating with a medium thickness and separate pickling pits. Classes 2 and 4 are mixes of the neighboring classes.

Figure 6. Schematic images of class 1, 3 and 5 coatings.

Pilot plant experiments

5 scaling tests were needed before the process was under control. Then the optimization test series was manganese phosphated and thoroughly examined in order to find the optimum process parameters, see table 1. From the optimization tests series O8 and O3 were chosen for evaluation in contact fatigue testing (gears) together with a series with no activation (O7 was not chosen due to high amount of pickling pits for its class). These three series showed coatings with spread in crystal size, coating thickness and number of pickling pits. The control samples which were manganese phosphated at the same time as the gears showed desired coatings for all three variants (see table 2 and figure 7).

Table 1. Results from the optimization series and from test without activation (beaker test). "No activation" was not part of the pilot plant test but indicates that it will generate large crystals, thick coatings and high amount of pickling.

Test	O1	O7	O4	O6	O2	O8	O5	O3	No activation
Conc. ativation salt A	low	low	high	high	high	high	low	low	-
Activation time	short	long	short	long	short	long	long	short	-
Conc. MnPh chemical	low	low	low	low	high	high	high	high	high
Average thickness	low	medium	low	medium	medium	low	low	medium	high
No. of pickling pits	low	high	medium	medium	low	low	low	medium	high
Crystal size	small Most even distribution	medium Even distribution	small Some defects	small - medium Large under, small above, Defects	small Rectangular crystals, Even distribution	small Even distribution	small Even distribution	medium Even distribution	large Even distribution
Class	**2**	**3**	**2**	**2**	**1**	**1**	**2**	**2-3**	**5**

Table 2. Manganese phosphating results of the process control samples (manganese phosphated simultaneously as the gears for contact fatigue testing).

Test	U8	U3	U0
Conc. activation salt A	high	low	-
Activation time	long	short	-
Conc. MnPh chemical	high	high	high
Average thickness	low	medium	high
No. of pickling pits	low	medium	high
Crystal size	small	medium	large
Class	**1**	**3**	**5**

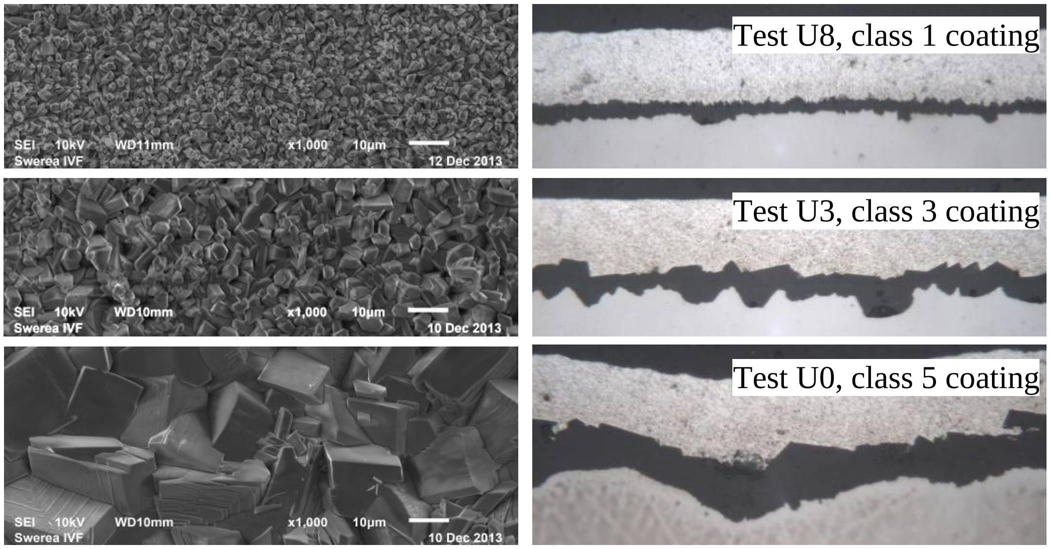
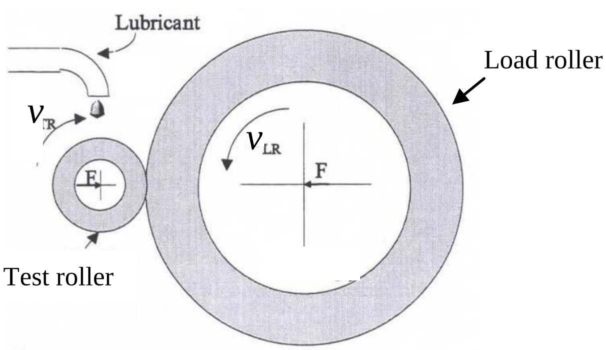


Figure 7. SEM images and cross sections of samples from the pitting test series.

5.2 Contact fatigue test (roller to roller)

The contact fatigue tests at Swerea KIAMB AB was performed in a roller to roller test bench, see figure 8. The parameters that can be varied are speed, load, oil temperature and slip.



$$Slip = \frac{v_{Tr} - v_{Lr}}{v_{Tr}}$$

Figure 8. Schematic view of test cell and definition of slip

The test rollers were machined from forging blanks, case hardened and ground to final shape. Some rollers were shot peened and/or manganese phosphated. The load rollers were manufactured in Ovako 825B and quenched and tempered to a hardness of 64 HRC. Four different crowning of the load rollers were used, 6, 21.5, 25 and 30 mm.

The testing showed that with the current testing condition, micro pitting was the dominating damage mechanism. Several trails with adjusted test parameters, polished load roller and changed slip were performed. The micropitting was still dominating even though some pitting was observed.

The contact pressure was increased and an extra fine polishing of the load rollers was performed. Pitting was observed in four of the six samples. This method proved to be the most reliable and resulted in pitting damages that could be evaluated. Unfortunately the test method with extra polished load rollers was not sufficient to produce pitting damages and to suppress formation of micropitting in manganese phosphated samples.

Several factors promoted micropitting, large slip, high temperature and lots of additives in the oil. If micropitting is formed on the roller the contact pressure is decreased by the increased contact area. This is contrary to the mechanisms in gears where micropitting instead might lead to increased local stresses and promote pitting. The fatigue cracks that would eventually have developed into pitting might be removed by micropitting. The formation of a track also results in reduced contact stress even if the applied load is constant. This stress might be below the threshold for pitting. Hence it is of vital importance to prevent micropitting during testing.

5.3 Contact fatigue testing (gears (FZG))

Due to the lack of pitting damages in the roller to roller test bench a decision was made by the steering group to use one of our back up options, FZG testing. The FZG test bench is of back-to-back type and is suitable to test the contact fatigue performance of spur and helical gears. Figure 9 shows the test bench and the gear data used for the tests. The testing was performed at Laboratory for Machine Tools and Production Engineering (WZL) of RWTH Aachen University.

The method used was based on FVA 371 with low viscosity gearbox oil (75W-80) at a temperature of 100 °C. The testing was performed until pitting occurred or the number of load cycles reached 40 000 000 (run out).

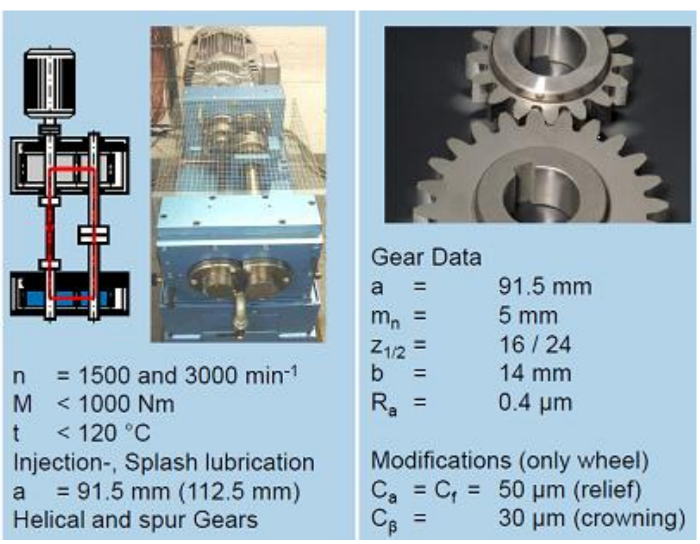


Figure 9. Experimental setup at WZL.

Figure 10 show that the manganese phosphate coating increased the pitting performance in the FZG testing. Class 3 coatings showed the best performance the chosen test levels (2.55 GPa and 2.7 GPa). This indicates that a moderate pickling with well defined pickling pits, medium sized crystals and somewhat thicker coating is more beneficial for the contact fatigue strength. This seems to make the running-in gentler and reduces the number of surface damages initiation points which ultimately leads to pitting damages. It is possible that the pickling pits in the metal surface facilitate the lubrication of the gear contact. This, in combination with a somewhat thicker coating which protects the surfaces more efficient, seems to increase the contact fatigue strength.

The class 5 coating showed very good performance but measurements after the testing showed that the profile deviation is too big to be considered valid (see figure 11). The surface pressure in the testing became too low due to the profile deviation hence class 5 was disqualified.

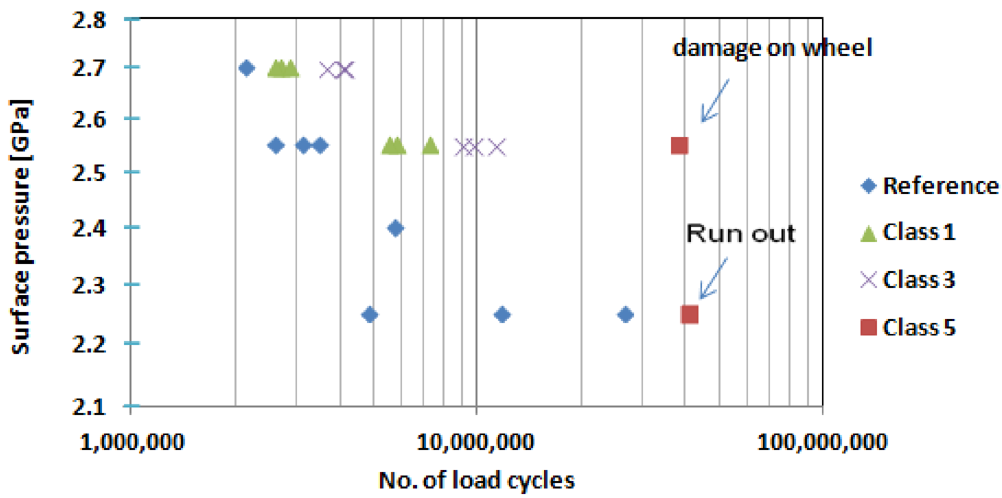


Figure 10. Contact fatigue test results. Class 5 was disqualified due to large profile deviation after testing.

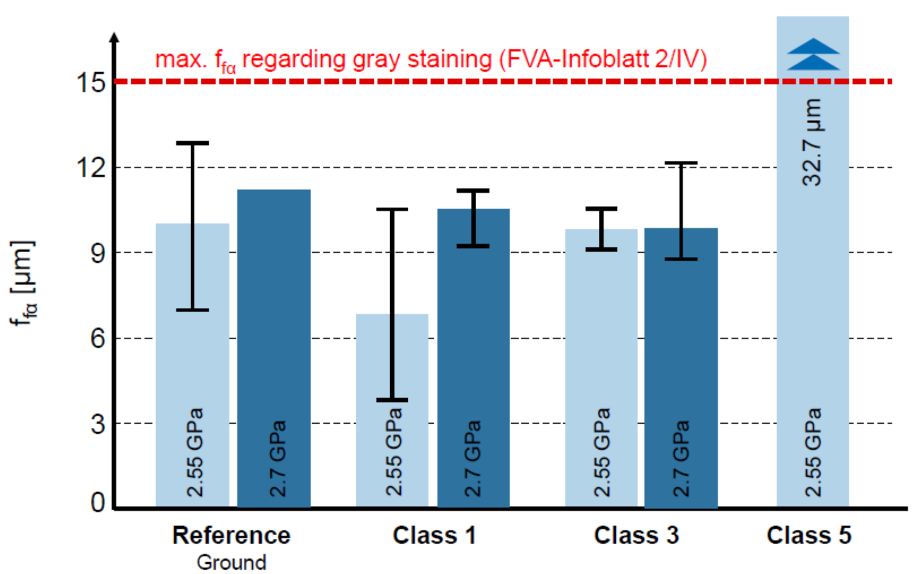


Figure 11. Form deviation of the pinion after testing.

5.4 Delivery to FFI-goals

The project's goal has in many ways contributed to the objectives of the FFI program. The gear test that has been developed and carried out will provide an opportunity to reduce costly and time-consuming full-scale rig testing. This increases the pace of the development and competitiveness of our products. Moreover, it helps to reduce development costs and free up resources that can be used more efficiently. By being able to increase the strength without increasing the weight, this will create the opportunity to reduce emissions from heavy transports. In addition, it is possible to reduce the viscosity of the gearbox oil which can further contribute to reducing fuel consumption and emissions. This enables Scania to compete with effective solutions for heavy transport. Furthermore, the project has shown that for certain components the manganese phosphating is not the best solution. Manganese phosphating has been removed in these cases and resulted in reduced cost of Scania and the customers.

To achieve the project goals and objectives of the program, there has been a close collaboration with Swerea KIMAB AB and Swerea IVF thus strengthening research and innovation environments where industry and research institutes are cooperating. Scania has also completed a master thesis which also led to collaboration with other academic institutions.

The project has contributed to the goals within the FFI-program as stated below.

- Strengthened the competitiveness of the automotive industry in Sweden
- Strengthened and facilitated industrially relevant development actions
- Supported and strengthened research and innovative environments
- Strengthened the cooperation between the automotive industry and research institutes.

In addition, two students from Aachen University made their practice on Scania thanks to the contacts built up during the FZG testing. Another student from Germany will begin an internship in the fall. The students were not directly working with this project but will still help to spread a positive image of Scania, which will help Scania to recruit skilled personnel domestic and abroad. In the end, this is important to maintain a strong position globally.

6. Dissemination and publications

6.1 Knowledge and results dissemination

The gear testing performed turned out to be more repeatable than we have seen previously in contact fatigue testing. Further verification is required but the method will continue to be used to save time in the full-scale rigs. Scania will buy this type of rig to render product development for gears more effectively. The results of the project will be used as input for fine tuning the test method and will be used on all kinds of gear development (material, geometry, surface treatment, etc.). The experiences from the process study have increased the knowledge regarding these types of surface treatments. This has improved Swerea IVF AB possibilities to offer other companies education within this field.

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6.2 Publications

Conference presentations

- Produktionsklusterkonferens 2013, Mötesplats för framtidens framgångsrika verkstäder, 2013
- Produktionsklusterkonferens 2014, Mötesplats för framtidens framgångsrika verkstäder, 2014

External education

- Course regarding phosphating, provided by Swerea IVF AB

Master thesis publication

- “The influence of copper on the quality of manganese phosphate coatings and the running-in of crown wheels and pinions”
  Paul Janik, 2010, Royal Institute of Technology, Material Science, Sweden

Computer software developed

- Leica Qwin macro for image analysis of surfaces and coatings

Project reports

- ”Rolling contact fatigue tests of ground, shot peened and manganese phosphated rings”
  Sven Haglund, 2013, KIMAB-2013-507, Swerea KIMAB AB, Sweden
- “Manganese phosphating for increased contact fatigue”
  Carolina Pettersson, 2014, project report 21829, Swerea IVF AB, Sweden
- “Increased Contact Fatigue by Manganese Phosphating”
  René Greschert, WZL RWTH Aachen, Germany

Internal reports

- Evaluation of manganese phosphating in axle applications - contact fatigue and chock load testing
  Scania reports: 7002990, 7003060, 7006627, 7006653, 7008964, 7010166, 7012623, 7014191, 7016441
- Evaluation of the scuffing performance of manganese phosphating in gearbox application
  Scania report 7012527, 7013959, 7019392
- Evaluation of manganese phosphating in gearbox application – contact fatigue testing in back to back rig (FZG type)
  Scania reports: 7012872, 7014535
- Material investigations of rollers and FZG gears
  Scania reports: 7023094, 7023088

Internal steering documents/guidelines

- STD4291, “Phosphate conversion coatings”, Scania Standard
- TB4221, “Manganese phosphated gears”, Scania Technical Regulation
- Reviewed and updated “PROCESSINSTRUKTION förtvätt och manganfosfatering”

Patent requests

- 19291, ”Betning av kulpeenad kugg”, Peter Björklund m.fl.
- 19290, "Fosfatering av kulpeenad kugg", Peter Björklund m.fl.

7. Conclusions and future research

From a general point of view the cooperation between Scania and Swerea IVF AB and Swerea KIMAB AB is well established and strengthened. The project results are used by all project partners.

In more detail the project has generated the following:

- Method for ranking and evaluating the manganese phosphating with respect to
    - Coating characteristics
    - Surface influence of the process
    - Contact fatigue strength properties
- Guideline/instruction for optimised manganese phosphate layer.
- A new method for evaluation and examination of coated surfaces.
- A screening method for testing of gears. This will shorten the development time and free resources in the full scale rigs that is used for final verification.
- Improved contact fatigue strength when using optimised manganese phosphating on spur and helical gears (gearbox) and using lower viscosity oils. This will generate the possibility to reduce fuel consumption.

The research performed within the project has shown that the manganese phosphating is beneficial for gearbox applications. Still it is important to continue the evaluation and verification especially in combination with different lubricants. This project will continue as an internal project and the cooperation with Swerea IVF AB and Swerea KIMAB AB will continue.

The FZG testing and evaluation of the manganese phosphated gears showed good and consistent results and contributed to the decision to invest in testing capacity at Scania. During 2014 there are plan to purchase two FZG test rigs which will increase the research possibilities for gears. The FZG rigs will decrease the development time and free resources in the full scale test benches that are used for final verification.

8. Participating parties and contact persons

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