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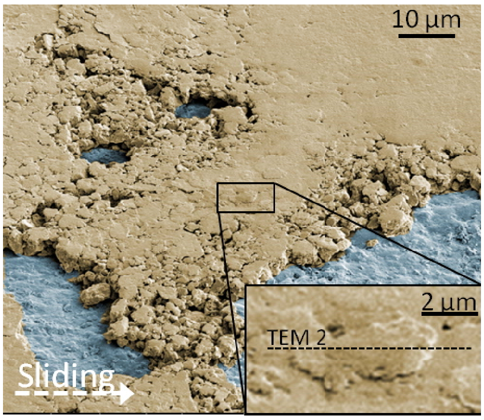
Optimisation of the contact surface and material choice of exhaust valve seat inserts and valve head seats for environment friendly heavy-duty engines





Final report

Project within vehicle development

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SCANIA

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Content

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1. Executive summary

The objective of the project has been to provide Scania with the increased knowledge necessary to optimise the material combinations in the valve/valve seat insert contact. Specifically, Scania must meet the new challenges of wear and the associated loss of efficiency occurring as a consequence of the reduction of particle flow through the valve, when adapting the motor to comply with Euro 6. The knowledge gained strengthens the position of Scania with respect both to future development of the valve system and with respect to the dialog with sub-contractors.

The project has been conducted in close cooperation between Scania CV and the Tribomaterials Group at Uppsala University. The Scania team was headed by Åsa Gustafson, with colleagues from the most relevant division within construction and testing. The Uppsala team included one full time PhD student (Peter Forsberg), one part time senior researcher (Patrick Hollman) and the head of the Tribomaterials group (Staffan Jacobson).

Research wise, Uppsala has provided microscopy investigations, surface analyses, design, manufacturing and tuning of a new test rig, development of an efficient test methodology, and running tests in the new rig. Further, Uppsala has, after consultation with Scania, been responsible for publications and presentations at conferences and work shops.

Scania first guided Uppsala into the complex world of valve systems and has continually provided “real” cases used valves, from field tests and motor cell tests, unused valves to be run in the test rig in Uppsala, provided data around the geometry and conditions of the valves in motors, etc.

The project has been very successful and generated valuable new knowledge, primarily around the great protective action of the emitted particles, in those systems where the form wear protective films. Further, new detailed information on how these films are formed and how high requirements must be set on systems that shall be capable of running well without the flow of particles. The designed lab test rig has proven to be very efficient and capable of producing interesting results in relatively limited time. The results have been presented at a number of national and international conferences and seminars, as well as in scientific journal papers. Finally, the project has established a new efficient cooperation between the Scania and Uppsala teams.

2. Background

The tribological conditions of exhaust valves in heavy-duty diesel engines are becoming increasingly tougher. Paradoxically, this is primarily due to the increasing demands on low emissions. The valves (the contact surfaces of the valve and the valve insert) are exposed to impact and microscopic sliding, under high temperature in corrosive atmospheres. The surfaces in this harsh contact used to be protected by the films spontaneously formed from soot, sulphur compounds and residues from fuel and oil. These films will here be called *tribofilms* [3,4].

With the extreme demands on low exhaust contamination and particle emissions now under way, the sources of the microscopic particles and contaminants must be strongly reduced or even eliminated, and consequently the flow through the valve will not offer the raw material to form the protective coating or tribofilm.

It must then be expected that the wear of the valve contact surfaces will increase substantially, in the way as already experienced in for example motors driven by compressed natural gas.

More than being a service life problem, the increased wear will result in deteriorated combustion conditions, which in turn will result in problems with polluted emissions. This deterioration is due to that the, initially optimised, volume in the combustion chamber grows as the valves must be lifted higher into the seat to seal efficiently. Further, the flow resistance for emptying the chamber through the opened valve becomes higher. Both these changes reduce the efficiency of the motor.

According to Euro6 and later regulations, the emission must be kept low during the whole service life of the motor, which results in that improved knowledge within the area is of extreme importance for Scania.

It is with this background the project has been conducted and also a new application of a prolongation/extension of the project has been applied for and approved.

The project started with a first meeting between the partners Scania CV and the Tribomaterials group at Uppsala University in March 2010 and the last project meeting was held in December 2012. A follow-up seminar, where the results will be presented for a larger group will be held at February 17 2013 at Scania. Phase 2 of the project is already up to speed.

3. Objective

The main objective of the project has been to increase the knowledge to the level needed to allow Scania optimise the material combinations in the valve/valve seat insert contact. Specifically, it is necessary to avoid those problems with wear and the associated loss of efficiency that occurs when the flow of particles through the valves becomes significantly reduced, when adopting to the strict emission regulations of Euro 6. This knowledge strengthens Scania's position for future development of the valve system and also put Scania in a better position for their dialog with sub-contractors.

Further the development of a new labscale rig test will give possibilities for an effective knowledge build-up, by being cheap, offering simpler control of the contact parameters and by being substantially quicker than motor cell testing. These advantages facilitate screening tests of numerous material candidates.

4. Project realization

Scania CV AB, Engine development, Basic engine and Materials Technology (*Scania)* have been responsible for executing the project in cooperation with the Tribomaterials group, which is a sub-group at the Department of Engineering Sciences at Uppsala University (*Uppsala*).

The project has been conducted in close cooperation, through a series of meetings in Uppsala and at Scania, completed by telephone meetings, plus a small number of seminars for a larger group of engineers at Scania. The Scania group has been headed by Åsa Gustafson with co-workers from the most relevant division within design and testing; Petter Kylefors, Dominique Debord, Daniel Lindberg and Ivil Hanna.

The Uppsala group has included a PhD student (Peter Forsberg), a senior researcher (Patrik Hollman) and the head of the Tribomaterials group (professor Staffan Jacobson).

Research wise, Uppsala has conducted the microscopy investigations, the surface analysis, design, manufacturing and methodology development of the new test rig, and all running of rig tests. Further, Uppsala has, after consultation with Scania, been responsible for publications and presentations at conferences and work shops.

Scania first guided Uppsala into the complex world of valve systems and has continually provided "real" cases used valves, from field tests and motor cell tests, unused valves to be run in the test rig in Uppsala. Scania has also provided experience and data around the geometry and conditions of the valves in motors, needed for an efficient and correct analysis of the test results. The analysis of all results from motor cell tests, field tests, rig tests and microanalysis has been discussed between the partners.

5. Results and deliverables

5.1 Delivery to FFI-goals

Simply stated, this project has contributed to almost all goals of FFI (see the following list.) A few point may be worth some extra words; Our strive to form an improve knowledge platform within the area *wear mechanisms of the valve system* will contribute to a more systematic procedure in future development work and for a stronger position of Scania's R&D towards international sub-contractors. The cooperation with Uppsala University will strengthen the focus on engines in Swedish materials research and will therefore give an improved international competitive level plus open up for future cooperation projects, since the partners have gained a better understanding of each other's competences and needs. This cooperation with the University world is expected to see increasing valued in the future of shape a more scientific approach to find solutions of critical technical barriers. Since the allowed development time for new solutions tightens, the need for cooperation, academic research and knowledge that can strengthen the industrial competence and facilitate development will grow.

As evident from the following sections, the project has contributed to the following points:

- Contributed to a continued competitive vehicle industry in Sweden
- Facilitated industrially relevant development actions
- Resulted in industrial technical development and competence development
- Contributed to strengthened R&D activities
- Contributed to concrete production improvements at Scania
- Supported research and innovative environments
- Supported the creation and implementation of new knowledge
- Strengthened the cooperation between the vehicle industry and Universities.

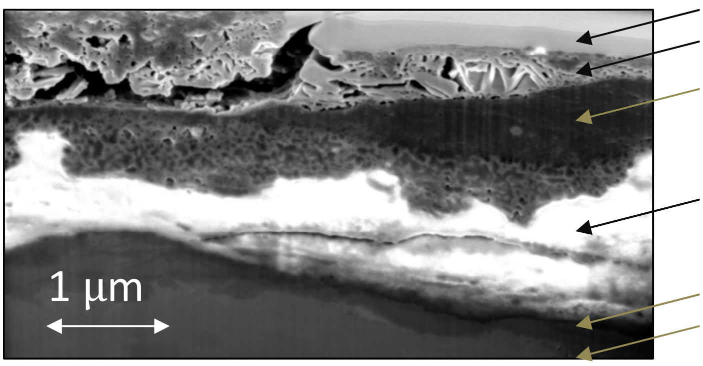
- Supported the national supply of competence plus the establishment of R&D at a competitive international level

5.2 Concrete results

The work has been successful, and provided increased knowledge of the area as well as useful and promising results. Valves and seats taken from the field and engine cell tests have been studied in detail, particularly with respect to the tribofilms formed, and the differences that can be observed between the different fuel types. Furthermore, a test was rig designed, tuned and delivered lots of interesting results. The main advantage of this rig compared to the established engine test cell is that it is quick and inexpensive, allowing more types of studies and well-controlled conditions.

Mapping of wear and tribofilm formation on valves from motor tests

Consistently for the valve system investigated, a protective tribofilm covering the sealing surfaces has been found on those systems that show low wear. This tribofilm usually include several different layers with different structure and composition, see Figure 2. Common to layers 2, 3 and 4 is that they contain calcium and zinc, which likely is derived from additives in the oil or fuel.



1. Metal layer that protected the cross section preparation
2. A porous top layer.
3. Compact layers with high carbon content.
4. Layer formed from small particles, partially charged due to poor conductivity.
5. Oxide.
6. Underlying Stellite material

Figure 1. Typical cross section through a field-tested. Layers 2-5 where formed during running and constitute the tribofilm in this case.

In several cases where we have found tribofilm on the surfaces, the underlying surface was untouched, while there are cases, as in the figure, where the underlying valve material also has an oxide film and an uneven structure. This suggests that the tribofilm is not constantly present, but rather that it is formed, becomes worn off, regenerates, etc. This makes it very complex to compare different systems, often with relatively unknown running cycles [1].

These mechanisms are very interesting and largely previously unknown. Knowledge of the parameters that are favourable and which are destructive to the construction and maintenance of a protective tribofilm is still incomplete, but increases gradually with the increasing number of tests in the test rig.

The new valve test rig

A test rig has been developed during the project and is now fully operational, see Figure 2. A hydraulic cylinder allows the valve movement and adds the force corresponding to the combustion pressure in the cylinder. A resistive heater heats the valve from below and heated air flows through the valve when it is open. In the preheated air, there is also the possibility of introducing preheated oil that evaporates when it is inserted. This enables us to vary a number of parameters that cannot be separated in the engine test cell.

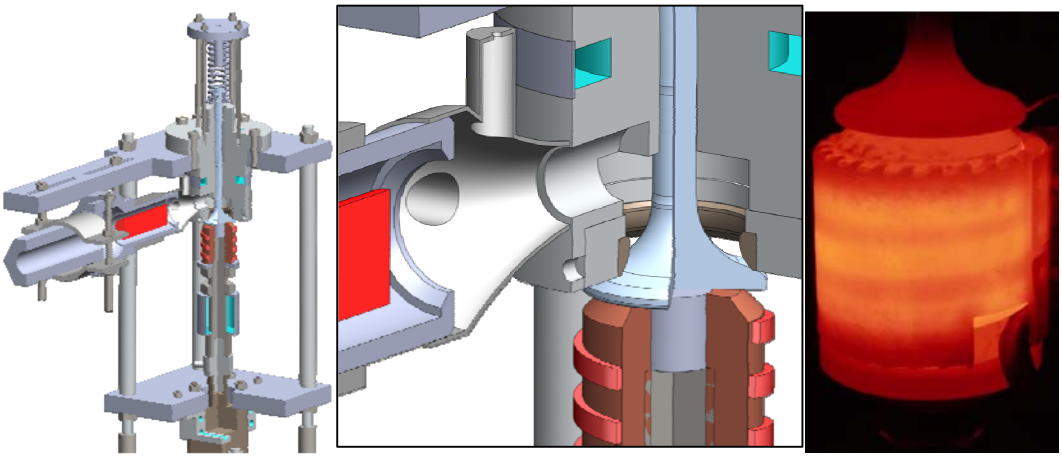


Figure 2. The valve test rig that was designed, manufactured and used within the project. The left picture shows and overview of the central parts, the middle picture shows the central parts in higher magnification while the right show the combined forcing body and heater during testing.

Another key advantage is that the test can be interrupted, parts removed, the surfaces evaluated, parts fitted, and the test can then be resumed. Something similar is not feasible in the engine test cell. In the rig, this evaluation of wear and surface structures can be performed at any wanted interval. When the machine is stopped, only a few relatively simple steps are needed to disassemble the valve and seat insert, see Figure 3.

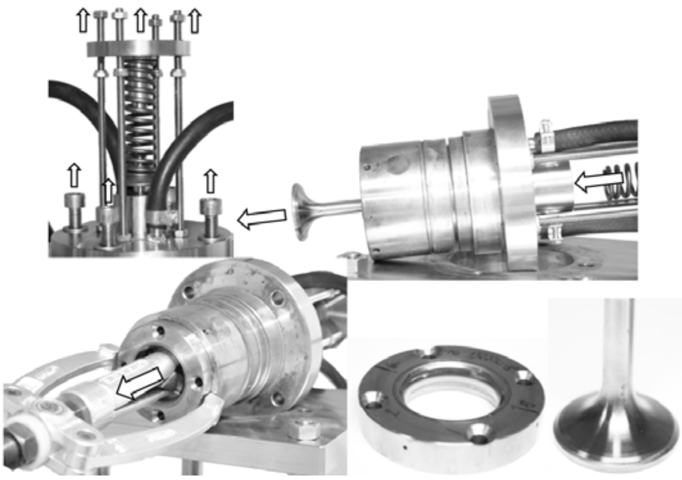


Figure 3. Demounting of valve and valve seat insert in a few simple steps.

By taking pictures of a variety of fixed positions on both the seat and the valve at each stop, a good image of the initial wear process is gained. A complete test including editing of the images is managed in one day. This contrasts strongly with the engine cell tests, which usually run over 400 hours (and often over 1000 hours) plus preparation, and are not suitable for repeated interruptions to study the gradual changes. An engine test is also very expensive compared to a rig test.

Results from the new valve test rig

After the initial tuning of the rig, several sharp test series have been performed. The first involved a number of different coatings the valves, and was run in a clean air atmosphere without oil mist. Figure 4 shows an example of the wear performance of an uncoated reference valve. Note the chipping of the outer edge due to fatigue, in c) and d) [4]. Some of the coatings showed better characteristics than the others. Unfortunately, the selected valve material proved to be too soft at the test temperature, and could not provide adequate support for the thin coatings. This is an interesting result in itself, but prevents strong conclusions to be drawn about the ability of the coating to improve the wear situation in the long run, see Figure 5. The initial wear values suggest that the PVD layers have the potential to improve the system, if also the substrate material and the counter surface are optimized. The tests clearly illustrate the importance of making a correct choice of materials in the coating of valve systems.

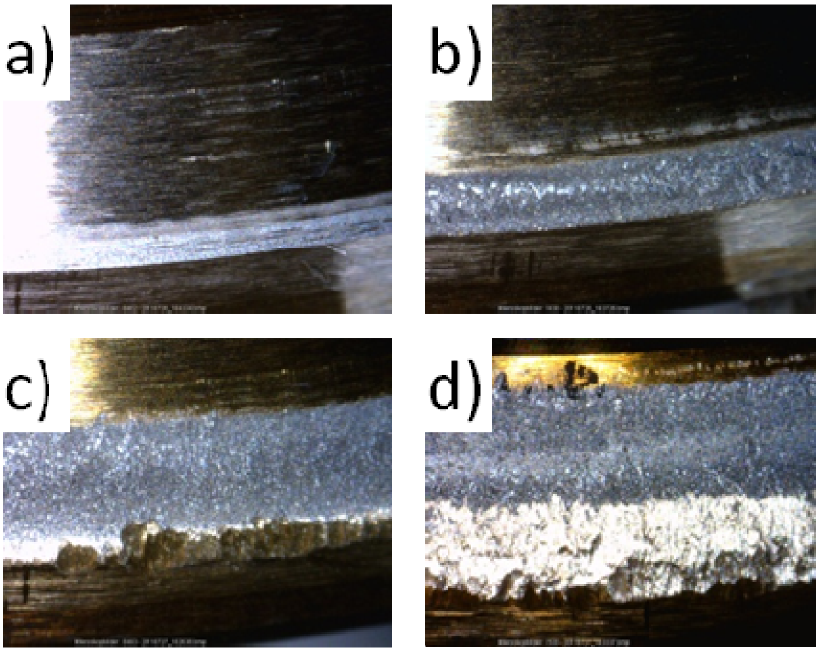


Figure 4. Examples of gradually increasing wear and final spallation of the contact surface of a valve, taken from a dry test in the rig. a) – d) show the appearance after 1000, 8000, 30 000 and 100 000 valve cycles respectively.

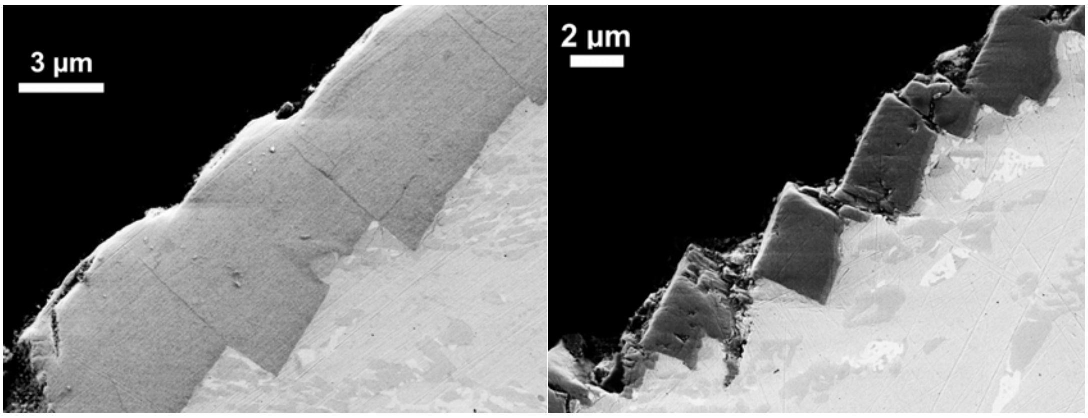


Figure 5. Examples of deterioration of PVD coatings on valves. The coatings have fractured, become turned and pressed down into the substrate by the contact forces. The primary cause to this is the inadequate support from the substrate (too low hardness) at the high operation temperature. Left: CrN coating, right: TiAlN coating.

Test series with inflow of oil mist have been successfully performed; see the example in Figure 6. The early results indicate that the rig can form tribofilms that are very similar to those formed in the engine, both in structure and composition. Detailed materials analysis of tribofilms suggests that they form from agglomerates of wear particles together with oil and unburned particles that land on the surface and form a protective film.

Figure 6. Examples of valves tested in the rig, using a flow of oil mist that has resulted in the formation of tribofilms. Top: overview. Left: valve run 100 000 cycles (i.e. as many cycles as in Fig. 4d) Right: valve run 500 000 cycles. Extremely low wear compared to the valves run in air.

Tests with oil mist showed that the tribofilm was very protective and reduced wear to near zero. Compare the pictures from a test where the valve has run 500,000 cycles where the wear was virtually zero (bottom right in Figure 6) with one run 100,000 cycles in conditions where a tribofilm did not form (Fig. 4).

A thorough analysis (SEM, TEM, XPS, Nanointentation) of tribofilms formed in the rig and formed on a field run valve, showed that in both cases they were softer than the underlying material and also showed many other similarities. Along the edges of the film, one can see traces of how it formed. Agglomerates of partially burned / vaporized residues from the combustion chamber (mainly residues from engine oil) sticks to surfaces and become stuck. New particles are added on top and over time form a complete film, see Figure 7. The tribofilm is with time densified and sheared out to become fully dense and composed of several different layers.

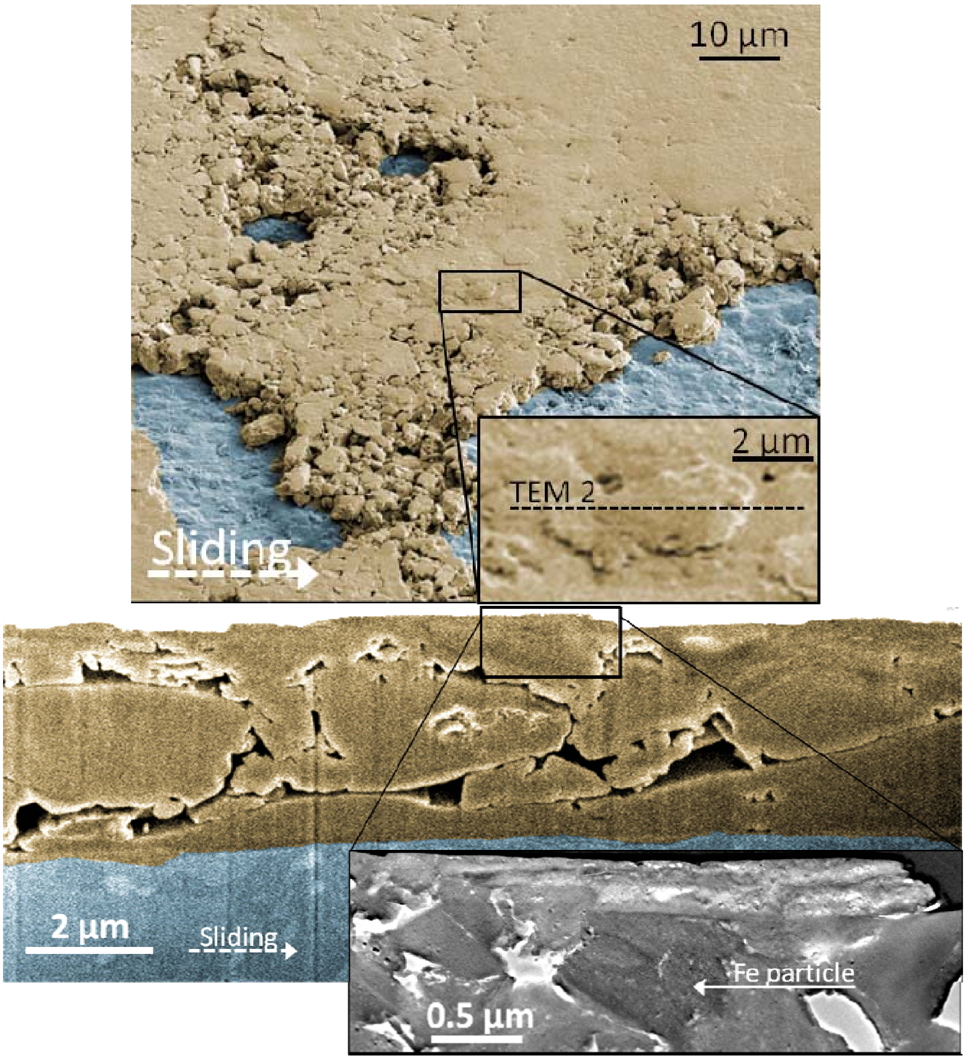


Figure 7. Tribofilm on the valve surface, build up from partly burned oil particles that have become stuck and squeezed together to form a partly dense and protecting film. The valve movement, involving impact and micro sliding, has executed the formation.

a) SEM showing the top surface close to the edge of a tribofilm. b) Cross section in SEM c) Transmission electron microscopy showing the structure of the tribofilm in cross section.

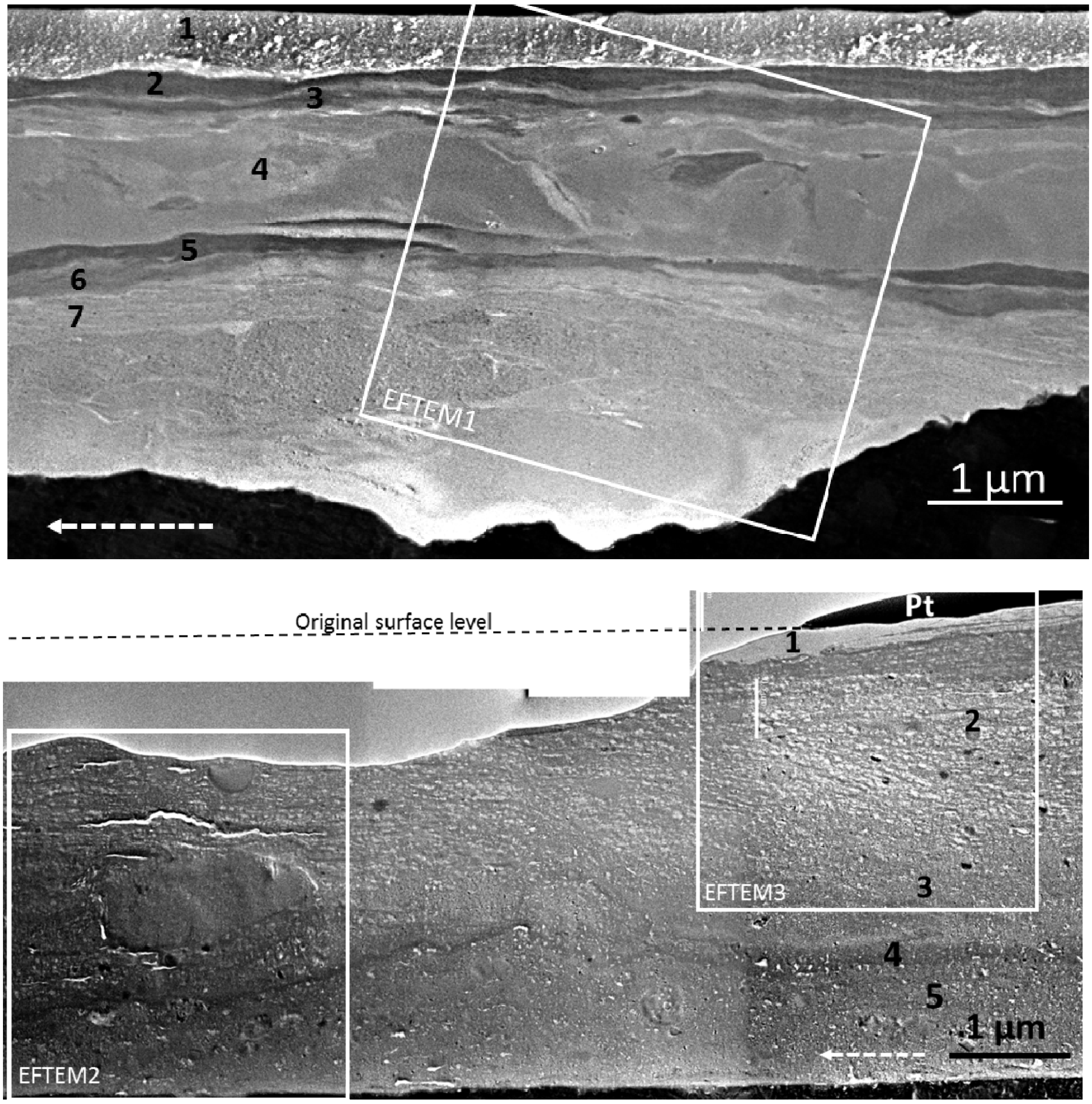


Figure 8. TEM cross section showing two dense and fully covering tribofilms, both including a number of layers plus smaller and larger included particles. Upper example: rig sample. Lower example: field tested valve. [WOM2013-papper]

An experimental technique to detect and measure the microslip at valve closing

The unique control capabilities of the valve test rig has made it possible to develop unique experimental knowledge about the relative motion between the valve surfaces during valve closure. It has long been known that there must be some sliding between the surfaces during the valve closing, it is not a pure impact. The movement arises because the main valve is deformed – it flexes - a little, by the increasing load. It has not been possible to measure this movement, but we have got to rely on relatively uncertain FEM estimates. In the rig we were able to perform a smart test, which showed that these estimates correspond well to the actual movement, see Figure 8. This knowledge allows a confident discussion of the wear mechanism, now that the sliding distance is known.

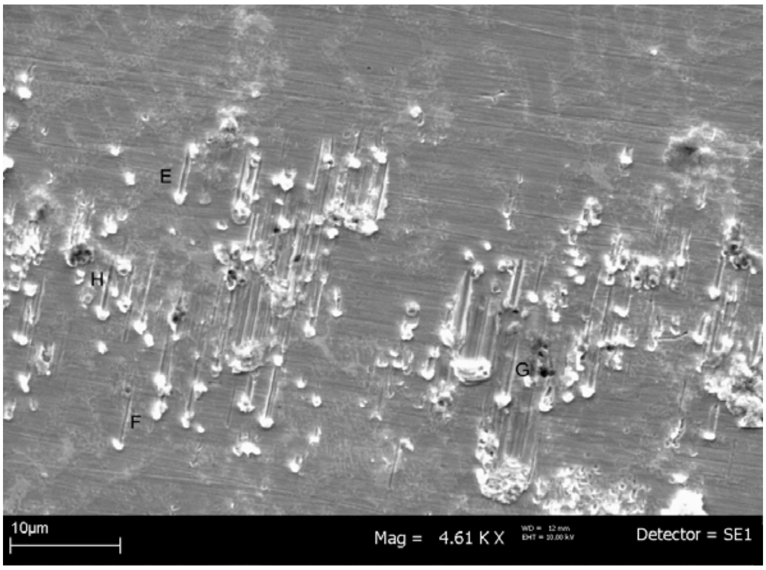


Figure 9. Seat surface of a valve after a test investigating the microsliding during a valve closing manoeuvre. Diamond particles were first distributed over the surface. Then the rig was run one single closing cycle. Scratches were thus formed on the surfaces, with a length corresponding to the local sliding distance, in this case roughly 5-10 µm.

6. Dissemination and publications

6.1 Knowledge and results dissemination

The results and the knowledge gained is, of course, primarily spread within the project, but the nature of the project has also made it possible to spread the knowledge very openly, at conferences, workshops, seminars, and also as interesting examples of applied engineering during classes in Uppsala and national graduate school courses in tribology .

The project's timeliness and universality in terms of environmental and energy-driven technological development has caused a great interest to hear about it at seminars and conferences, including outside the relatively narrow circle of people interested in just the valve mechanisms tribology. For the Tribomaterials group in Uppsala, the project has been very important and central to the current "project portfolio" that includes more projects with similar backgrounds. One example is the European project HELIOS, which focuses on technology that would allow a conversion of the current ship diesel engine operating with todays high sulphur fuel HFO (heavy fuel oil), to completely sulphur free natural gas. Uppsala’s part of the project involves the study of changes in wear mechanisms when the protective sulphur based tribofilms no longer form on cylinder liners and piston rings, and what materials changes could compensate for the aggressive wear. These two projects (and even more related projects in Uppsala) naturally enriches each other.

In addition to the regular internal project meetings and presentations, the project and part of the results presented at *Ångströms tribomaterialdagar* 8-9 September 2010 in Uppsala, at *Danish-Swedish Tribology Days* 17-18 November 2010 in Copenhagen, at *International Conference of Wear of Materials*, Philadelphia 4–7 April 2011, *Ångströms tribomaterialdagar* 14-15 June 2011, *Skandinaviska tribologidagarna*, 8-10 November 2011 in Trollhättan, *at SAE 2012 World Congress & Exhibition*, Detroit, 24-26 April 2012 and at *Ångströms tribomaterialdagar* 22-23 May 2012 in Uppsala.

National and Scandinavian work shops and seminars (printed documentation in form of PowerPoint hand-outs)

1. Peter Forsberg, Nötningsmekanismer hos avgasventilsystem i moderna lastbilsmotorer, Ångströms tribomaterialdagar, 2010
2. Peter Forsberg, Wear mechanisms of exhaust valve systems on modern truck engines, Danish-Swedish Tribology Days 2010 i Köpenhamn
3. Peter Forsberg; Avgasventilnötning - En djupdykning i mekanismerna bakom de extrema nötningsskillnader som kan uppstå mellan olika cylindrar i samma motor, Ångströms tribomaterialdagar, Uppsala, 2011
4. Forsberg, P., P. Hollman, and S. Jacobson, Wear simulation and evaluation of heavy duty exhaust valve systems in a test rig, Skandinaviska tribologidagarna, 2011 i Trollhättan
5. Peter Forsberg; Skyddande tribofilmer från föroreningspartiklar? En ventilriggsundersökning om konsekvenser av renare avgaser, Ångströms tribomaterialdagar, Uppsala, 2012

6.2 Publications

The project results have been published in scientific and technical journals. In several cases, the same material was first presented orally at conferences (and prnted in the conference proceedings) and has then been accepted for publication in journals. Peter Forsberg is planning to present his PhD thesis within this project September 2013, mainly based on the following articles and three more under work.

Journal papers

6. Forsberg, P., F. Gustavsson, P. Hollman, and S. Jacobson, "Comparison and analysis of protective tribofilms found on heavy duty exhaust valves from field service and made in a test rig", Wear (2013): accepted for publication.
7. Forsberg, P., P. Hollman, and S. Jacobson, "Wear Study of Coated Heavy Duty Exhaust Valve Systems in a Experimental Test Rig". SAE Technical Paper 2012-01-0546 (2012)
8. Forsberg, P., P. Hollman, and S. Jacobson, "Wear mechanism study of exhaust valve system in modern heavy duty combustion engines". Wear 271, no. 9-10 (2011): 2477-84.

International conference papers and posters

9. Forsberg, P., F. Gustavsson, P. Hollman, and S. Jacobson. "Comparison and analysis of protective tribofilms found on heavy duty exhaust valves from field service and made in a test rig", Wear of Materials. Portland, USA, 2013.
10. Gustavsson, F., V. Renman, P. Forsberg, A. Hieke, and S. Jacobson. "Smart DLC Top Coating for Reduction of Counter Surface Wear in Fuel Contact." Paper presented at Tribology, Faraday Discussion 156, Southampton, U.K., 2012.
11. Forsberg, P., P. Hollman, and S. Jacobson. "Wear Study of Coated Heavy Duty Exhaust Valve Systems in a Experimental Test Rig." In SAE 2012 World Congress & Exhibition, 2012.

12. Forsberg, P., P. Hollman, and S. Jacobson, "Heavy duty exhaust valve simulation and evaluation in a test rig", Presented at Nordtrib, Trondheim, Norway, 2012.
13. Forsberg, P., P. Hollman, and S. Jacobson. "Protective tribofilm build up from exhaust residues on the surface on exhaust valve systems in a test rig." In Nordtrib, Trondheim, Norway, 2012.
14. Forsberg, P., and S. Jacobson, "On the formation of a protective tribofilm build up from the exhaust residues on the sealing surface on heavy duty exhaust valve systems in a test rig", Presented at Nordtrib, Trondheim, Norway, 2012.

7. Conclusions and future research

• Cooperation between the people involved at Scania CV and at Uppsala University is now well established and effective.
• A working test rig has been designed with the help of both parties' expertise, and very quickly reached a level where interesting studies can be conducted. A clear indicator of the rig's advantages is that Scania is now building another one, for use at Scania, funded outside FFI project.
• The stringent requirements that must be placed on the underlying valve materials for modern ceramic PVD layer to be used, has been clearly demonstrated.
• The strongly protective effect of tribofilms have been clearly demonstrated. The contact becomes extremely aggressive and abrasive, in the absence of the film forming elements.
• The analysis of the tribofilms has resulted in that we now understand much more about how they form and which components are most important.
• A wealth of new knowledge and methodology has been generated with both partners that will be used in future research and development projects
• The project has been very stimulating for the student, as it involved diverse research, and has given broad knowledge and experience of relevant industrial development.

Continued research

The successful concept of the project led to an application for and prolongation, and some extension of the project. The parties fairly early realised that the first project was all too short for all the good fruits to be harvested. The area is very complex and the initial knowledge was been limited (not just the within project, but also in terms of state of the art in the research literature). The application was accepted by the FFI and the project reported here has now seamlessly transferred into the new project.

It is noted that the area is becoming increasingly important. The development of future emission standards in Euro 7 has begun and requirements are further tightening. The requirements for absence from particles, combustion soot and low NOx levels become extreme and probably also limits for carbon dioxide emissions will be added. The requirements for the motors to maintain their low emissions, even after long periods of use are tightened.

It is also important to provide the capability when conditions change, not only for new engines, but also when the installed base of 1 000 000's of engines turn into use of new fuels and fuel mixtures, depending on the market. Different types of fuel will increase, as the share of the transport sector will shift from fossil fuels to biofuels. The project therefore broadened to include not only the exhaust side (like the just-completed stage), but also the intake valves and intake seats. The exhaust side primarily plays a role in how efficiently the engine uses fuel by minimizing gas exchange losses. The inlet side however, plays a decisive role in controlling intake airflow for optimum combustion, i.e. maximum efficiency and minimal soot production. In future emission legislations, requirements for very low wear rate on the inlet valves are expected to increase. Unfortunately, the valve and seat designs optimized for optimum combustion results in poor wear characteristics. New tools are therefore required. Improved knowledge of the optimization of surfaces, and the choice of combinations of materials and surface coatings in valve contacts, can offer these tools. Since the inlet side operates at a lower temperature than the exhaust side then modifications of the rig will be minimal. The PhD student Peter Forsberg will present his thesis in September. A new student will be adopted in February and work in tandem with Peter, and then take over the project in the fall. Specific studies that are planned during Peters time remaining in the project:

• The type of engine oil and the amount used varies between engine types and different parts of the world market. A specific study of the impact on the construction of the protective tribofilm will be performed in the rig.

• investigation and surface analysis of the intake valves from representative wear cases (high / low / etc.) collected from the field and motor cell tests.

• When the tribofilm formation is better understood (i.e. at what parameters the film most easily built up) a study of degradation mechanisms will bed initiated.

A deeper understanding of how and why the protective tribofilm is formed and destructed can be used as an indication of what kind of running modes and situations that may be preferable in future engines to protect against valve wear.

8. Participating parties and contact persons

The project was conducted by Scania CV AB and Uppsala University, Division of applied materials science, The Tribomaterials Group.

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