FFI
Fordonsstrategisk
Forskning och Innovation

Optimisation of material selection and contact surfaces of valves and valve seat inserts to facilitate environment friendly heavy-duty engines.

Final report Dnr. 2011-03653

Project within Vehicle development

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SCANIA

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Content

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1. Executive summary

This project has aimed to provide Scania the increased knowledge necessary to optimize combinations of materials and the structural design of the valve / valve seat contact. The project has been a direct deepening and widening of the previous project: No. 2009-01208, and therefore in essence shares both objective and methodology of this. When the previous final report was written (January 2013) this project phase had already been applied for and granted. This naturally leads to partly overlapping reports from the two project phases. The focus in this second final report is on reporting the methodology and new results that have emerged.

Interestingly, the project is based on the wear problems that arise when demands for cleaner emissions tightened. Specifically, Scania must fend off the problems with wear and associated efficiency losses arising when the flow of particles through the valves is reduced, which occurs as a result of adaptation to Euro 6 levels of particulate emissions.

The knowledge generated strengthens Scania's position for future development of the valve system and provide a better position for dialogue with suppliers.

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 (Robin Elo), and the head of the Tribomaterials group (Staffan Jacobson). During the first months Robin was working together with PhD student Peter Forsberg, who presented his thesis based on his work within the project in September 2013, and during the same months also with part time senior researcher (Patrick Hollman)

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 workshops. 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, particularly about the strong protective effect of emitted particles on the valve systems, where they form and maintain wear resistant films. Further, a new efficient test equipment and testing methodologies has developed. The test method is unique, has given new knowledge and has received attention from more engine manufacturers.

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 both exhaust valves and intake valves of heavy diesel engines become increasingly difficult. Paradoxically, it is caused by the increasing demands for low emissions. The valve, i.e. the contact surfaces between the seat and the valve, are subjected to impact stresses and short sliding contact (typically around 10 microns slip), under high temperatures in corrosive atmospheres. The surfaces of this troublesome contact have previously been protected by the coatings spontaneous build-up of soot, sulphur compounds and residuals from the lubricating oil and fuel. These coatings are here called tribofilms.

With the extreme demands on the clean exhaust that is about to be introduced, the sources of these microscopic particles and pollutants significantly must be reduced or completely eliminated, and consequently the flow through the valve will no longer offer the raw material for the protective coating / tribofilm.

It must be expected that the wear of the valve surfaces increase significantly, in the same way as already experienced e.g. in engines powered by compressed natural gas.

In addition to providing a wear-life problem, the increased wear result in degraded combustion conditions, which in turn leads to emission problems. The reason for this deterioration is that - it initially optimized - volume of the combustion chamber grows when the valves must move further up into the seat to seal. Moreover, the flow resistance to empty the combustion products through the open valve increases. Both these changes reduce the efficiency of the engine.

Beginning with the Euro 6 level, emissions must be kept low during the entire engine life, which means that increased knowledge in the field is of utmost importance to Scania. It is against this background that both the first and second project parts have been performed.

The project's first phase began with a meeting between the parties Scania CV and Tribomaterials group at Uppsala University in 2010 and the last project meeting of the first part was held in December 2012. This second project part started seamlessly and a last meeting is scheduled at Scania February 2015. Already when this second phase of the project began, we knew then that it was based on a successful concept. The cooperation between the involved persons at Scania CV and at Uppsala University was well established and effective. A fruitful rig methodology was designed with the help of both parties' expertise, and had already reached a level where interesting and unique studies were performed.

3. Objective

By the end of the first project phase the parties felt that the project was too short to allow all the good fruits to be harvested. The area is very complex and fundamental knowledge was limited before the start of the project (not just within project group, but also largely seen to state-of-the-art in research literature).

It was also found that the area is becoming increasingly important. The development of future emission legislation (Euro 7) has been initiated and requirements are further tightening. Extremely tough demands are expected for freedom from particles and combustion residues plus low nitric oxide levels and probably also rules on limiting carbon dioxide emissions. The requirements that the engines must maintain their low emissions even after prolonged use will be further tightened.

Moreover, Scania needs readiness to act when conditions change, not only for new engines, but also when the installed base of millions engines begins to be used with new fuels and fuel mixtures, depending on the market. The fuel diversity will increase as part of the transport sector will switch from fossil fuels to biofuels.

The project has broadened to include not only the exhaust side (as in the first project phase) but also the intake valves and inlet seats. The exhaust side has primarily a role to play in how efficiently the engine uses the fuel by minimizing gas exchange losses. The inlet side plays a crucial role in controlling the intake air flow, in such a way that the combustion is optimized both from an efficiency perspective and to minimise soot formation. Future emission legislation will also lead to requirements for very low wear rates of the inlet valves. Unfortunately, today valve and seat designs optimized towards these targets result in poor wear characteristics. We therefore need new tools that allow simultaneous optimization towards both goals. Improved knowledge of the optimization of surfaces, and appropriate combinations of materials and coatings in the contacting surfaces of the valves, can offer these tools. A deeper understanding the builds-up and break-down the protective tribofilm can be used as an indication of what kind of operating modes and situations that may be preferable in future engines to protect against valve wear.

4. Project realization

Scania CV AB, Engine development, Basic engine and Materials Technology has 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.

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 PhD students (first Peter Forsberg then Robin Elo), 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 workshops.

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

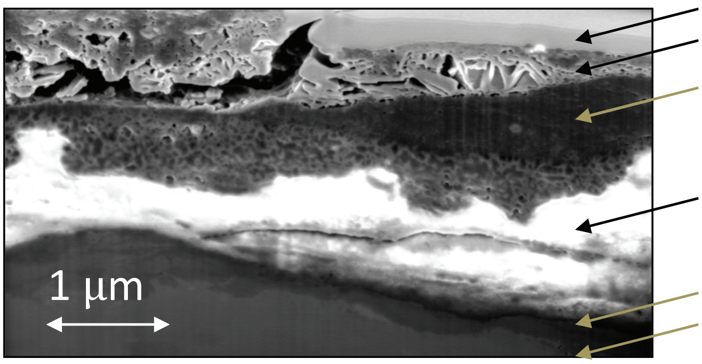
5.2 Concrete results

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. Within this second project stage, focus has moved from exhaust valves toward inlet valves.

Furthermore, a test has been 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. Within this second project stage, the rig has been developed to allow more realistic and well-controlled studies of the dynamics of tribofilm formation. Here we can only give samples of all the concrete results, focusing on the second phase of the project. The 7 published scientific articles and Peter Forsberg's thesis offer a more comprehensive description of all the results achieved over the course of the two projects.

Mapping of wear and tribofilm formation on valves from motor tests

Consistently for the valve system investigated, from field, motor cell and the rig tests, a protective tribofilm covering the sealing surfaces has been found on all those systems that show low wear. This tribofilm usually includes several different layers of different structure and composition, see Figure 1. 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, become worn off, regenerates, etc. This makes it very complex to compare different systems, often with relatively unknown running cycles. These mechanisms are very interesting and largely previously unknown.

The new valve test rig

A test rig has been developed during the project and generated a wealth of results, 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. The flow is then complemented by oil residues including uncombusted particles, mainly formed by oil additives. The test enables us to vary a number of parameters that cannot be separated in the engine test cell.

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.

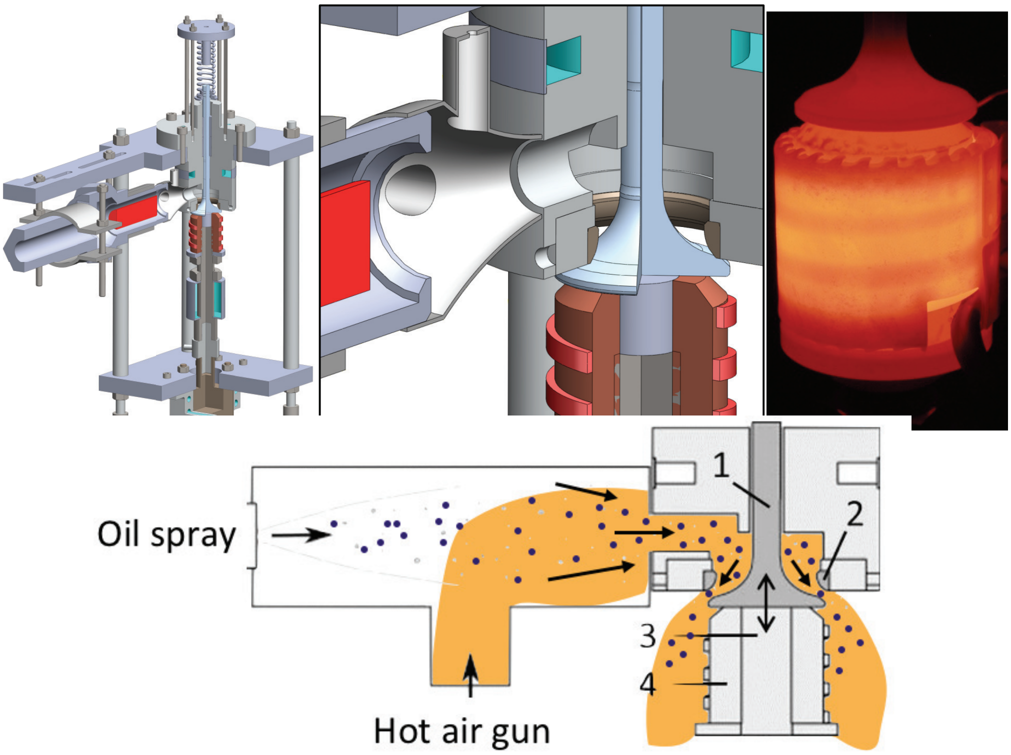


Figure 2. The valve test rig that was designed, manufactured and used within the project. The left picture shows and overview of the central parts, the middle picture shows the central parts in higher magnification while the right show the combined forcing body and heater during testing. The lower drawing shows the flow through the operating valve. The flow contains hot air with a small addition oil mist including additive-based particles. It is mainly these particles that tend to stick to the sealing surfaces, where they become squeezed and gradually form the tribofilm.

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

Several series of test runs have been performed in which variations in the addition of oil mist have used in diverse ways to generate new knowledge. An interesting test series illustrates the differences between running "dry", i.e. without oil mist, with oil mist, but with a pure synthetic oil without additives, and with oil mist of a fully formulated engine oil. It turned out, as expected, that the dry contact leads to excessive wear of both sealing surfaces, see the example in Figures 3 and 4.

Further, it was found that both the type and amount of oil in the flow (0.05 or 0.5 ml oil / 500 l air corresponding to ppm levels of oil in the hot air flow) had effects on the film formation. Most interestingly, it demonstrated a big difference in film formation between oil without additives and with additivated, fully formulated oil.

Fig. 3 Photos of valves run "dry", and with oil mists flowing through the operating valve.

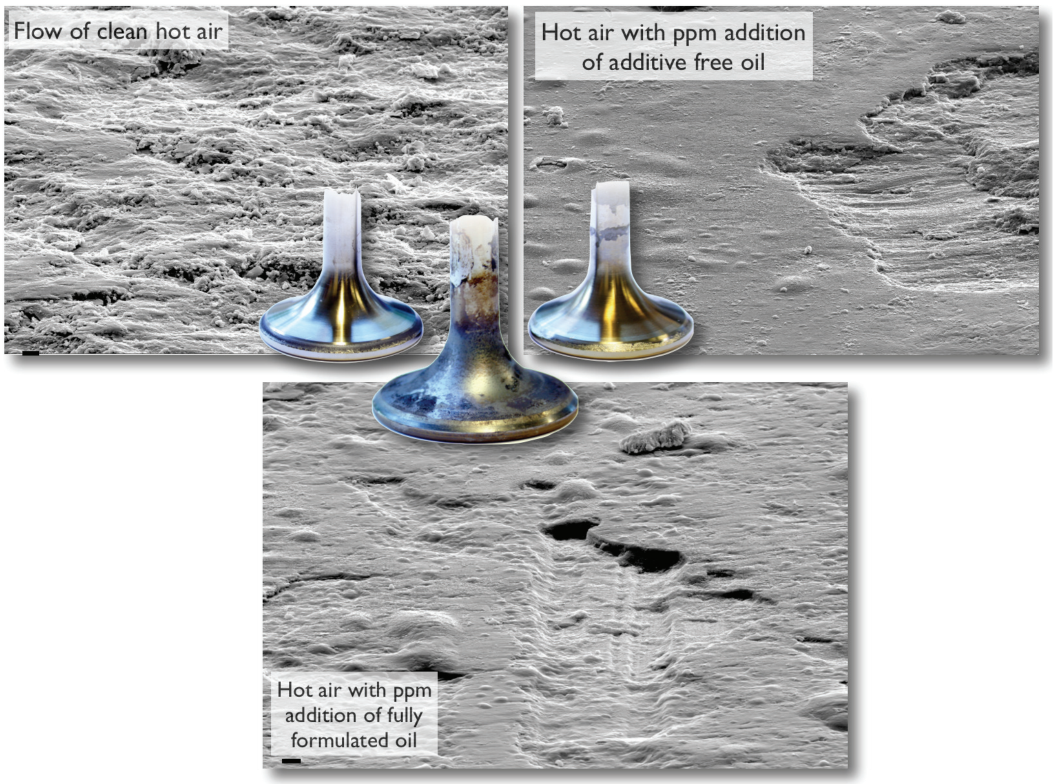


Fig.4 SEM Micrographs of the valves in Fig. 3, showing details of the worn sealing surfaces of on the valves. Tribofilms were formed in both cases with oil mist, but in the case of pure additive free synthetic oil the film is formed from agglomerated and mechanically worked wear debris. This film relatively easily spalls off, and therefore do not offer and efficient protection. The film formed with the fully formulated oil has a composition dominated by the additive constituents, mechanically worked into a film offering very good protection from wear

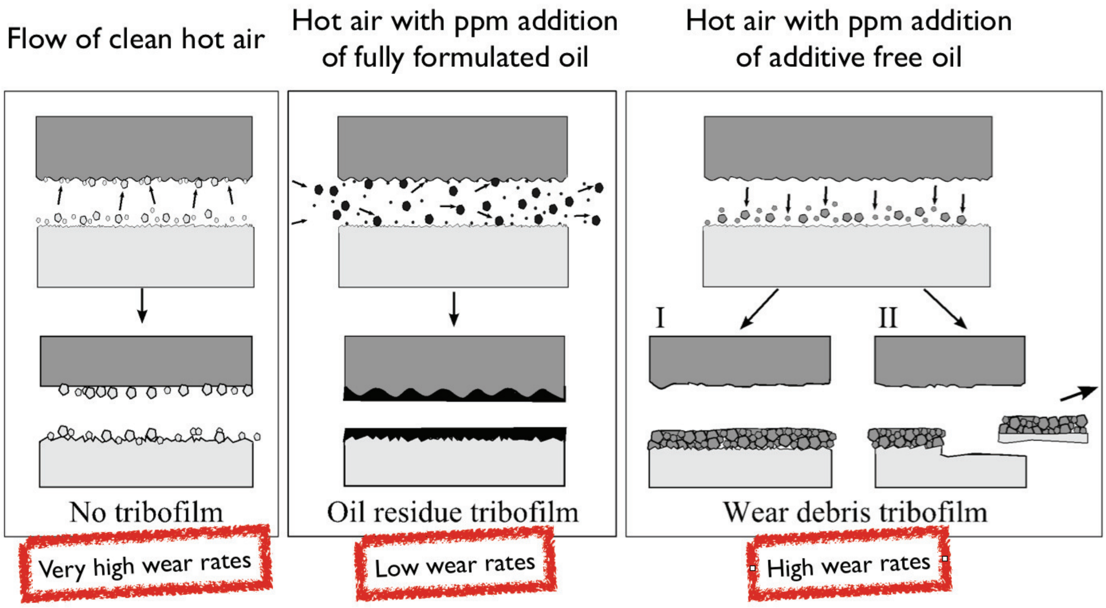


Fig. 5. Different emission flows lead to very different surface modification mechanism, as proposed by the three types above. (a) Mechanism occurring in the "driest" case, i.e. the Reference tests without any oil addition. Severe wear where wear particles – primarily from the valve surface – are found spread all over the contact surfaces. (b) Mechanism dominating for the fully formulated oils, resulting in a smooth protecting oil residue tribofilm. (c) Mechanism dominating for the non-additivated oil, involving formation of a smooth wear debris tribofilm on the valve by agglomeration of wear particles originating from the valve seat insert.

These test results may play an important role in the development of future valve designs. The different atmospheres generated, with parts per million mixes of oil in the hot air have triggered very different surface modifications:

1. Both fully formulated oils resulted in the formation of oil residue tribofilm in the high flow case. This led to protection of the surfaces and a mild polishing effect, instead of wear. The lowest flows of these oils resulted in a too thin tribofilm, which did not offer as good protection.
2. The PAO oil without any additives did not result in the formation of tribofilms based on oil residues. Instead, it promoted agglomeration of wear particles, forming a wear debris tribofilm on the valve. The film had a tendency to fracture and locally become sheared off, leading to accelerated wear. The shearing off behaviour seems to be accelerated by an increased flow of the additive free oil.
3. The dry references samples exhibited the most severe wear. Both the valve and the valve seat insert surfaces became covered with mostly oxidized wear particles, giving them a rough appearance. Without the presence of oil, no tribofilms formed and thus no protection of the surfaces was given.

Interestingly, it is not the *lubricating properties* of the oils, but their *ability to form a protective tribofilm* that is crucial for reducing the wear. With the clean combustion of future engines – where the oil additives will be reduced and the oil consumption kept to a minimum – the sealing surfaces of the exhaust valves will suffer a more severe wear situation. Future valve designs will therefore need surfaces optimized to make maximum use of the limited amount of combustion residues available.

Dynamics

The dynamics of the formation and breakdown processes of protective tribofilms on the closing surfaces of engine exhaust valves have also been studied in detail. Four phases were identified. The first two occur while tribofilm forming elements were supplied, in the form of an oil mist being added to a hot air stream passing the valves. The last two occur when the supply was cut off.

1. *Formation* – Oil residue particles become trapped on the surface, agglomerated, and then smeared out to form a more and more covering tribofilm.
2. *Equilibrium* – The tribofilm coverage stabilises when almost fully covering. Two film types are found, one carbon-based and one additive-based, dominated by calcium and phosphorous.
3. *Breakdown* – The carbon-based films are quickly removed, while the additive film wears off gradually at a much slower rate.
4. *Wear of exposed valve material* – Eventually the protective tribofilm locally becomes worn through, leading to severe wear and oxidization of the valve surface.

Interestingly, the protective qualities of the additive tribofilm were distinctly improved by prolonging the equilibrium phase, i.e. running the samples for more cycles while having the supply of oil mist passing the valve. Obviously this made an already fully covering additive-based film more durable. The carbon-based film seems to have very weak protective properties, and is rapidly lost once the oil mist supply is turned off.
The present results are unique in giving information about the wear resistance and protective properties of these types of tribofilms. It has previously been shown that they offer wear protection, in situations when the formation cannot be separated from the breakdown stages. Now it is also shown that they offer an efficient protection over large number of cycles also when no formation is possible. This suggests an opportunity to use different forms of controlled formation stages to maintain an established initial protective tribofilm. This might offer a solution to the challenge of keeping a very long wear life while radically reducing the emission of particulate matter.

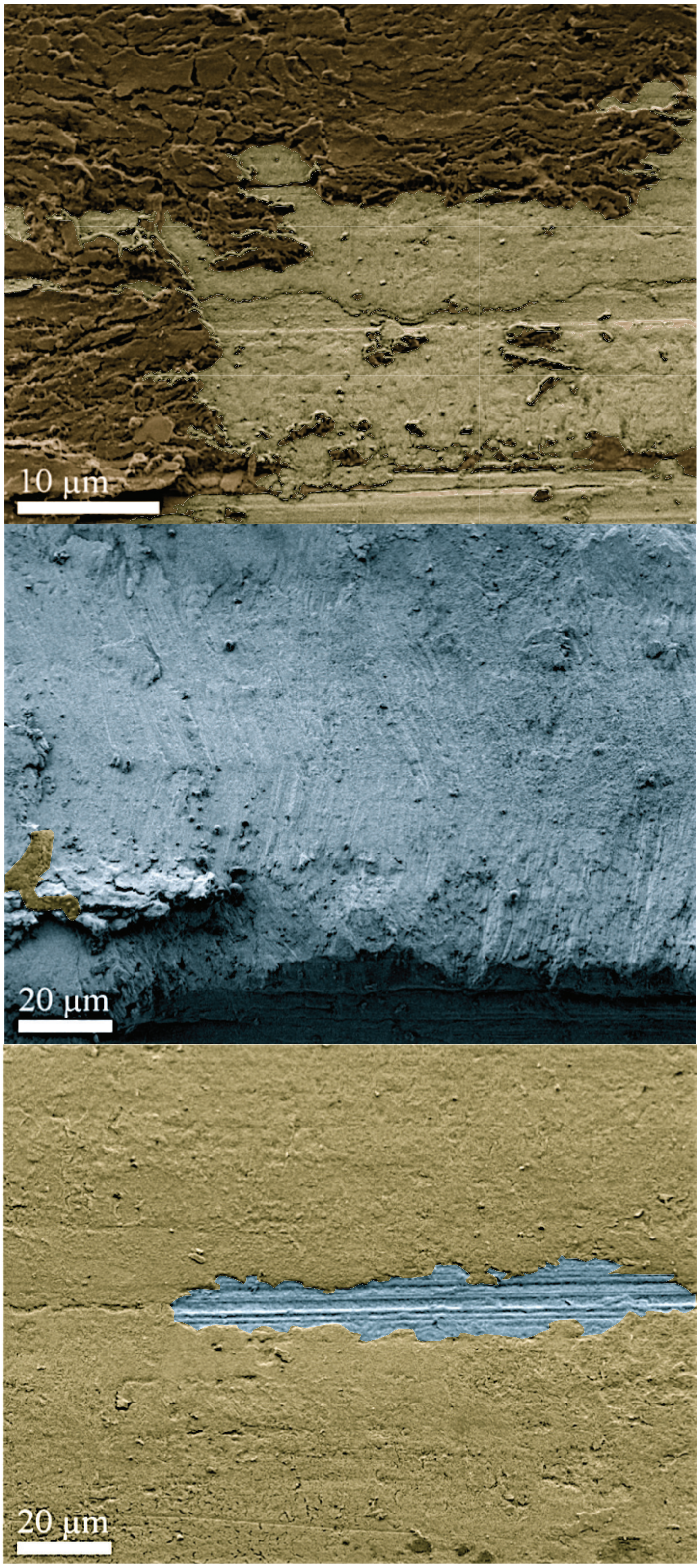


Fig 6. Appearance of the sealing surface of valves after different stages of formation and degradation of tribofilm.
a) As early as after only 1000 closing cycles, particles have agglomerated and become smeared out to partially cover larger parts of the surface. The darker film is a thicker carbon-based film and the lighter a thinner additive based film.

b) Sample run for 10,000 cycles with oil followed by 10,000 without oil mist. The film formed during 10,000 cycles has not been stable enough to protect properly, but the metal surface has become severely damaged by wear and corrosion.

c) Sample run for 100,000 cycles with oil followed by 10,000 without. Here, the 10 times more worked additive-based tribofilm is still offering very good protection. The counter surface has slid downwards as the valve closes.

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 enrich each other.

In addition to the regular internal project meetings and presentations, the project and part of the results have been presented and discussed at several national and international conferences and seminars.

Invited keynote lecture at international conference

Staffan Jacobson, *The delicate balance of tribofilm formation on combustion engine valves*, Friction, Wear and Wear Protection conference, May 2014 in Karlsruhe, Germany

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

1. Robin Elo, "Motorventilernas nötningsskydd – helt taget ur luften?", Ångströms tribomaterialdagar, Ångströms tribomaterialdagar, Uppsala 2014
2. Peter Forsberg, Ventilerna i förbränningsmotorer – en växade tribologisk utmaning, Ångströms tribomaterialdagar, Uppsala, 2013
3. Peter Forsberg; Skyddande tribofilmer från föroreningspartiklar? En ventilriggsundersökning om konsekvenser av renare avgaser, Ångströms tribomaterialdagar, Uppsala, 2012
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; Avgasventilnötning - En djupdykning i mekanismerna bakom de extrema nötningsskillnader som kan uppstå mellan olika cylindrar i samma motor, Ångströms tribomaterialdagar, Uppsala, 2011

6. Peter Forsberg, Wear mechanisms of exhaust valve systems on modern truck engines, Danish-Swedish Tribology Days 2010 i Köpenhamn
7. Peter Forsberg, Nötningsmekanismer hos avgasventilsystem i moderna lastbilsmotorer, Ångströms tribomaterialdagar, 2010

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 printed in the conference proceedings) and has then been accepted for publication in journals. Peter Forsberg presented his PhD thesis in September 2013, mainly based on the following articles a number of the below articles.

PhD Thesis

Forsberg, P., Combustion Valve Wear: A Tribological Study of Combustion Valve Sealing Interfaces, (Uppsala University, Acta Universitatis Upsaliensis, 2013).

Journal papers

1. Elo, R. and Jacobson, S., Formation and breakdown of oil residue tribofilms protecting the valves of diesel engines, accepted for publication, Wear 2015
2. Forsberg, P., Elo, R. and Jacobson, S., The Importance of Oil and Particle Flow for Exhaust Valve Wear – an Experimental Study, Tribology International 69 (2014) 176-83.
3. Forsberg, P., Debord, D. and Jacobson, S., Quantification of Combustion Valve Sealing Interface Sliding—a Novel Experimental Technique and Simulations, Tribology International 69 (2014) 150-55.
4. Forsberg, P., Hollman, P. and Jacobson, S., Combustion Valve Simulation Rig with Particle Flow, Lubrication Science, submittted 2014
5. Forsberg, P., Gustavsson, F., Hollman, P. and Jacobson, S., Comparison and Analysis of Protective Tribofilms Found on Heavy Duty Exhaust Valves from Field Service and Made in a Test Rig, Wear 302 (2013) 1351-59.
6. 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)
7. 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

1. Robin Elo, Staffan Jacobson, "Effect of particle flow and gas temperature on the wear of engine valves", International Tribology Conference 2015, Tokyo, Japan, accepted abstract
2. Robin Elo, Staffan Jacobson, "Formation and breakdown of oil residue tribofilms protecting the valves of diesel engines", Wear of Materials 2015, Toronto, Canada, April 2015, Poster
3. Robin Elo, Staffan Jacobson, "Formation and degradation of protective tribofilms on diesel engine valve surfaces", Nordtrib 2014, Århus, Denmark
4. Robin Elo, Staffan Jacobson, "Wear mechanism study of intake valve system in modern heavy duty combustion engines", Asiatrib 2014, India, – Presentation och extended abstract
5. Robin Elo, Staffan Jacobson, "Wear mechanism differences of intake valves within heavy duty combustion engines", SAE PF&L 2014 – Presentation
6. Forsberg, P., Gustavsson, F., Hollman, P. and Jacobson, S., Comparison and Analysis of Protective Tribofilms Found on Heavy Duty Exhaust Valves from Field Service and Made in a Test Rig, in "Wear of Materials" (Portland, USA, 2013).

7. 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.
8. 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.
9. Forsberg, P., P. Hollman, and S. Jacobson, "Heavy duty exhaust valve simulation and evaluation in a test rig", Presented at Nordtrib, Trondheim, Norway, 2012.
10. 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.
11. 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

- The 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 quickly reached a level where interesting and unique studies have been conducted.
- The strongly protective effect of tribofilms has 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 rig has proven to mimic the essential parts of the valve conditions in real engine operation, so that results can be used to predict and understand the "reality".
- The test rig is very fast and very cheap compared to performing similar tests in the motor cell or field test.
- Rig testing creates tribological films similar to those formed during actual operation, and has been able to demonstrate the impact of decisive changes or complete elimination of the films
- The strongly protective effect of the tribofilms has been clearly demonstrated. The tribological contact is extremely aggressive and wearing, in the absence of the film-forming elements.
- Due to the analysis of the tribofilms, we now understand much more about how they arise and which components are most important.
- We have generated unique knowledge of tribofilm dynamics; How fast can they formed? Do they change with time at conditions of steady flow of particles? How quickly do they break down if the particle flow is cut off?
- Importantly, we have been able to show that the gross wear rate is many times higher than the resulting wear. If no tribofilm is created, and then constitute the surface layer that is worn and maintained by additional particles), the wear life would be a small fraction of what it is today.
- The project has been very stimulating for the PhD students, as it involved diverse research, and has given broad knowledge and experience of relevant industrial development.

Continued research

The project is now being completed in its present form. At Scania development of the valves is on-going, partly based on the project results. For the Tribomaterials group the research continues with a similar focus, using the same methodology and test rig, but now with Wärtsilä as a financier. The research now focuses on the valve conditions of their large diesel engines for ships and power generators.

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.

Contact persons:
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Uppsala University: Professor Staffan Jacobson, staffan.jacobson@angstrom.uu.se, 018-471 30 80

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