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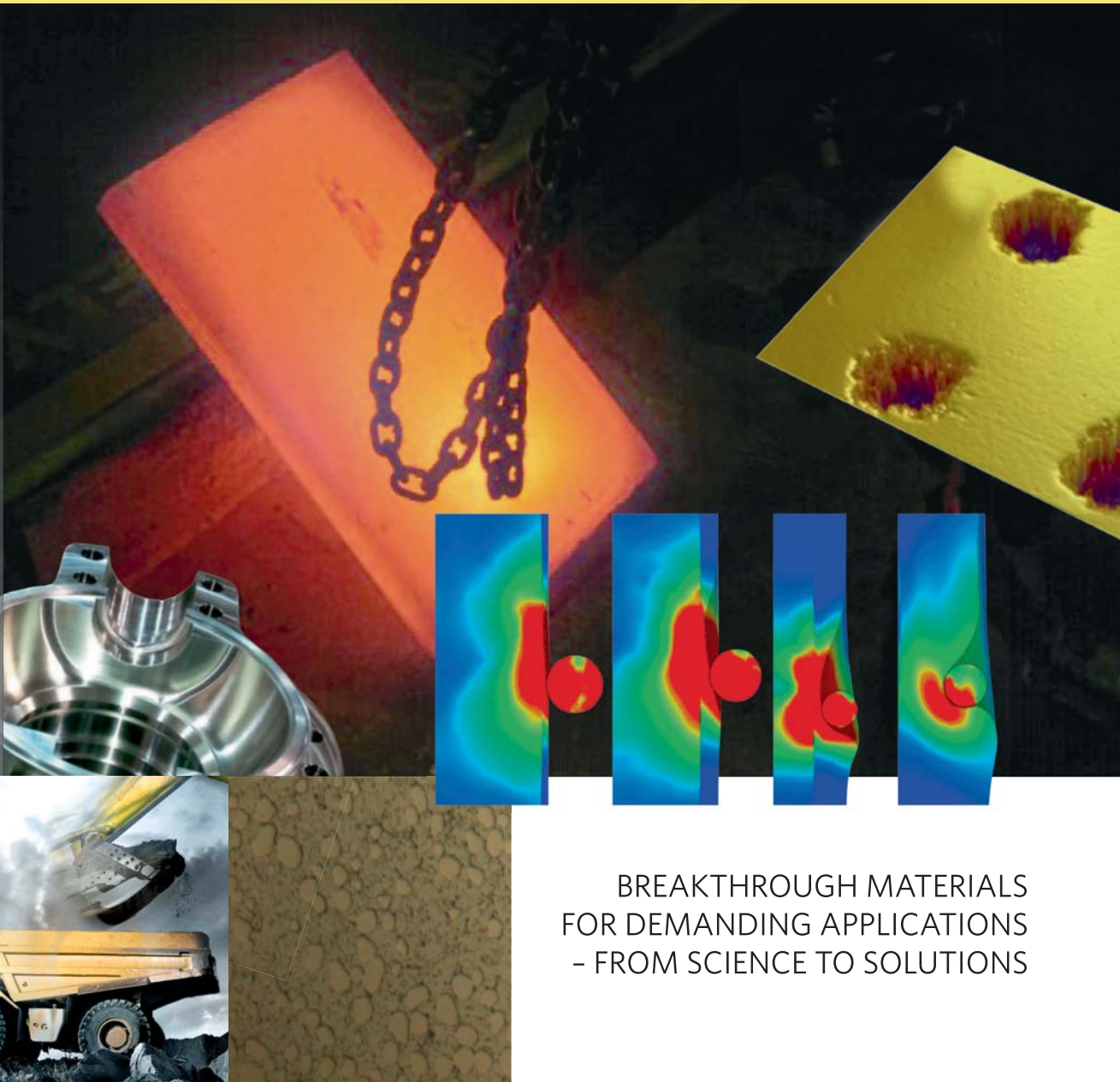
FINAL REPORT 3/2014

FIMECC PUBLICATIONS SERIES NO. 3

Demanding Applications –DEMAPP

2009-2014



BREAKTHROUGH MATERIALS FOR DEMANDING APPLICATIONS – FROM SCIENCE TO SOLUTIONS

FINAL REPORT 3/2014

Demanding Applications – DEMAPP

FIMECC
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PROJECT HIGHLIGHTS | FACTS AND FIGURES

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EXECUTIVE SUMMARY

FIMECC DEMAPP (2009–2014) is an industry-led public-private partnership programme (PPP) focusing on application-driven R&D of advanced materials for extreme service conditions. The target has been to tackle challenges related to critical wear, corrosion, friction and fatigue and to develop novel breakthrough materials solutions for the demanding applications in e.g. the process, energy and engineering industry. Building deep understanding of both the specific demanding application conditions and the related physical phenomena, FIMECC DEMAPP has provided great results, forming a solid basis for novel competitive solutions and product differentiation for Finnish industry.

A **need-based approach** has guided FIMECC DEMAPP research work in solving the most critical problems. Combining the knowledge and efforts of our excellent research consortium, we have been able to make crucial breakthrough results that, in many cases, have already led to rapid implementation in products – thanks to the systematic and committed efforts of the companies involved.

Sustainability and safety aspects have been key drivers for the development. Direct costs of material failures, replacements of components, increased work and time, and loss of productivity, as well as indirect losses of energy and increased environmental burden, are real challenges in everyday business. With catastrophic failures there is also the risk of human losses. Our new Cleantech innovations will bring significant improvement in energy efficiency, environmental sustainability and safety in demanding industrial applications.

Great results with high industrial impact have been achieved over a wide range of applications. For example, developing key enablers for a complete family of *wear-resistant and ultra-high-strength steels (by Ruukki Metals)* bringing e.g. energy-efficient, light solutions for transport as well as safety and new performance for harsh crushing and

mining applications. The novel *nickel-free corrosion-resistant stainless steel (by Outokumpu)* brings a new cost-effective and high-performance material to applications ranging from wall panels to exhaust systems and household equipment. *New cast aluminium alloys* (by Alteams) with 50% better thermal conductivity over the state-of-the-art, in turn solve critical problems of heat removal in electronic housing, base station equipment, etc., contributing to the energy-efficiency, reliability and lifetime of the devices.

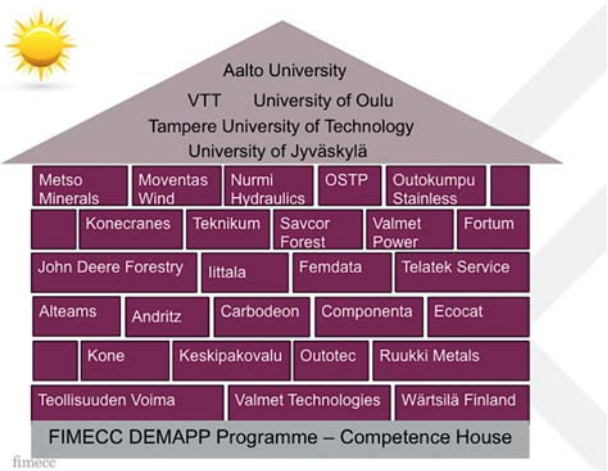
Further examples from the friction theme indicate the industrial relevance of the research results: 50% reduction of wind turbine transmission friction and wear and 30% improved torque density (Moventas) based on the use of carbon nanomaterials; 35% reduced friction through optimised surface topography of water-removal elements in paper machines (Valmet Technologies); 80% reduced wear by implementation of advanced composite coatings on hoisting wheels in wire contact for elevators and cranes (Kone, Konecranes), as well as new design guidelines based on friction modelling for more accurate prediction of fretting damage in medium-speed diesel engines (Wärtsilä). Developing a holistic calculation methodology for evaluating the global effects of friction on fuel consumption of passenger cars (VTT Technical Research Centre of Finland), followed by other case studies on heavy duty vehicles and paper machines, was highly recognised and referred internationally.

New science enabling these result examples has been worked out in a **true multi-disciplinary co-operation** between the active FIMECC DEMAPP consortium and our international partners, through extensive experiments and using the latest methodologies. Going beyond the state-of-the-art, we have also developed a set of application-specific wear-testing equipment and modelling tools to enable us to tackle the critical phenomena precisely. All breakthrough results, highlighted above through industrial relevance, are based on new scientific discoveries and important new understanding of mechanisms and behaviour of advanced materials in specific wear, corrosion, friction or fatigue conditions. One important part of the FIMECC DEMAPP research mode is that we have introduced multi-scale modelling as a concrete part of the R&D work. Making systematic experiments together with application-specific modelling, we have created more comprehensive understanding, especially of wear and friction, and shown that the development cycle can be made clearly faster – with better results.

Communication and implementation of the results has played a key role in FIMECC DEMAPP. From the very beginning, the programme management has paid special attention to ensuring that all players within this large research consortium are informed and involved – and committed to work towards the common goals. Our special events, including Impact Days (selling and buying fresh results), speed-dating sessions (building new co-operation) and wider annual seminars with careful results-harvesting and positive challenging of each other, have served as a platform for open and fruitful co-operation and co-creation. Preparing dedicated articles in professional media on FIMECC DEMAPP research themes and key challenges, and extensively concerning results already in the early phase of development, has helped to identify the most relevant results and bring them systematically towards application. The high commitment and real future needs of the companies have been a key driver for rapid implementation.

DEMAPP has been effective in bringing relevant results from science towards business, and building a base for the renewal of the Finnish metals and engineering industry. The best practices, the lessons learnt in terms of a highly co-operative working mode in the real FIMECC spirit, as well as making need-based application-driven materials research together using multi-scale modelling, form an asset that in the future will be of great value to Finnish industry and the research society. The new Breakthrough materials programmes (FIMECC BSA and HYBRIDS) have been successfully launched from this solid platform.

Have a closer look at the results highlights, and the stories behind them, in the five research themes ("projects") of FIMECC DEMAPP and its 18 sub-projects.



PROGRAMME FACT SHEET

Partners: 26 companies from Finnish Metals and engineering industry,
5 universities/research institutes

Programme duration 15.9.2009–30.9.2014

Volume: 37 MEUR (funded by participating companies and Tekes,
the Finnish Funding Agency for Innovation)

Projects (= 5 main research themes)

P1 Wear-resistant Materials and Solutions
4 Sub-projects
P2 New Corrosion Resistant Materials and Solutions
4 Sub-projects
P3 Extreme Service Conditions
2 Sub-projects
P4 Friction and Energy
6 Sub-projects
P5 Production Technologies for Demanding Applications
2 Sub-projects

Programme management:
Markku Heino and Vilja Vara (Laura Kauhanen 2009–2011), Spinverse Ltd.

Programme Management Committee (PMC) :
Kalle Kantola, FIMECC Oy/CTO (Chairman, 2013–2014)
Seppo Tikkanen, FIMECC Oy/CTO (Chairman, 2009–2013)
Jukka Kömi, Ruukki Metals Oy
Jukka Säynäjäkangas, Outokumpu Stainless Oy
Tero Taulavuori, Outokumpu Stainless Oy (2009)
Pekka Siitonen, Metso Minerals Oy (2013–2014)
Marke Kallio, Metso Minerals Oy (2009–2013)
Aulis Silvonen, Wärtsilä Finland Oy
Juha Koskiniemi, Andritz Oy (2013–2014)
Carl-Gustav Berg, Andritz Oy (2009–2013)
Veli-Tapani Kuokkala, Tampere University of Technology
Pekka Pohjanne, VTT Technical Research Centre of Finland
David Porter, University of Oulu (2012–2014)
Pentti Karjalainen, University of Oulu (2009–2012)
Simo-Pekka Hannula, Aalto University

Tekes contact persons:
Sisko Sipilä (2012–2014)
Pasi Viitanen (2009–2012)

PREFACE

Solve problems worth solving!

The world is full of interesting areas and topics to be discovered. Where resources are limited, efforts need to be focused on areas in which breakthrough discoveries can create the most value. Although the way results are achieved is not always as important as the results themselves, it is evident that the best way is the one enabling the greatest results in the most effective manner.

We at FIMECC believe that focusing on the most challenging problems, and gathering the best people to solve the most beneficial of them, is the key to success and real breakthroughs. Our recipe is result-oriented co-creation, in other words creating results together effectively through efficient use of the individual strengths of each member of the consortium.

This operating methodology has shown its value, as we can see from this FIMECC DEMAPP final report. The FIMECC DEMAPP programme is also an excellent example of the true co-operation culture that is a critical success factor for industry-wide impact. I would like to thank the FIMECC DEMAPP consortium for these great achievements, and programme managers Markku Heino and Vilja Vara for their excellent efforts in enabling effective programme work. I also express my gratitude to the programme's main financier, the Finnish Funding Agency for Innovation Tekes, whose support has enabled the execution of this risk-intensive research programme.

Beyond this programme, the great results and the culture and networks that have been created live on, both within the industry and in FIMECC's new material programmes: Breakthrough Steel and Applications (BSA) and Hybrids Materials (HYBRIDS).

Let's enjoy these great co-created results, and carry on with solving the problems that are worth solving!

Dr Kalle Kantola
CTO
FIMECC Ltd

Demanding Applications called for a special PPP – Professional People with Passion

Five years ago we had an exciting plan for a new research programme called FIMECC DEMAPP – consisting of 18 individual (sub-)projects set up together to tackle challenging research problems that were defined by the 26 companies and 11 research groups involved. Today we have a recognised, target-oriented FIMECC DEMAPP research community serving as a proven example of a spearhead PPP (Public-Private Partnership), capable of need-based development of advanced materials and manufacturing technologies, and effective implementation of results into products that renew industries.

Our systematic, application-driven research work on wear, friction, corrosion and extreme service conditions has led to the great results reported in this publication. Completely new ultra-high-strength steels or nickel-free corrosion-resistant steels; thermally conductive aluminium castings; various concrete solutions for reducing friction and/or wear in wind turbines, paper machines, hydraulics, diesel engines, cranes and elevators; specific chlorine-trapping coatings or electrochemical protection systems for corrosion protection in biorefineries and process and energy industry... these are just a few examples of novel cutting-edge solutions co-created together for industry. But it is not only about industry – these results are based on crucial new scientific findings and knowledge, created together. As a matter of fact, forming and running a FIMECC DEMAPP research community of more than 150 researchers (a good mix from industry and academia) – all working hand-in hand on relevant, focused research topics – is a great result in itself.

The co-creative working mode and trust we have succeeded in building together has boosted our multi-disciplinary research co-operation towards a variety of significant results – results that have been transferred effectively from science to business. One important system-level result is the concrete integration of multiscale modelling as part of R&D work – combined with systematic experiments and application know-how, we have created comprehensive, deep understanding, especially of wear and friction, and shown that the development cycle can be made faster and with better results.

Communication and implementation of the results has played a key role in FIMECC DEMAPP. From the very beginning, we have paid special attention to ensuring that all players within this large research

consortium are informed and involved – and committed to work for the common goals. Our special events – including Impact Days (selling and buying fresh results), speed-dating sessions (building new co-operation) and wider annual seminars with careful results-harvesting and positive challenging of each other – have served as a platform for open and fruitful co-operation and co-creation. Building news articles in professional media on the research themes and key challenges, extensively concerning FIMECC DEMAPP results already in the early phase of development, has helped to identify the most relevant results and bring them systematically towards implementation.

Best practices, lessons learnt, a highly co-operative working mode, and the co-creation of need-based, application-driven materials research that makes use of multi-scale modelling, all form a strong invisible asset that serves as a base for the future renewal of Finnish industry and the research community. The new FIMECC Breakthrough materials programmes (FIMECC BSA and HYBRIDS) have already taken off from this solid, but elastic platform. The ultimate impact of FIMECC DEMAPP is therefore yet to come.

"Though we can be happy about the achievements today, it is worth mentioning that we have also overcome many obstacles together. The FIMECC DEMAPP consortium has displayed *great strength* and commitment, showing itself to be *multiresistant in demanding conditions* when faced with the challenging economic and innovation political environment. By being open-minded, through *frictionless* co-operation and persistent pursuit of the things we have believed in, we have together achieved great results with real impact. This has surely been a journey worth taking."

I wish to thank all of you who have contributed to the programme. It has been a pleasure to work with you in making FIMECC DEMAPP a special PPP – thanks to Professional People with Passion.

Dr Markku Heino
Programme Manager
Spinverse Ltd

STAKEHOLDERS' PERSPECTIVES

Shok 'n' Roll – from Science to Solutions

One of the biggest issues in conducting high-quality research at universities and other research institutions in Finland has been the lack of sufficient long-term funding. Not any more, thanks to SHOKs! The five-year SHOK programmes, such as FIMECC's Demanding Applications (DEMAPP), have presented totally new opportunities for raising scientific basic research, and more industry-oriented applied research, to an entirely new level. One of the main reasons for the success of SHOKs, and especially of the FIMECC DEMAPP programme, is the long tradition of close collaboration between universities and industry in the field of Materials Science and Engineering. Though the research goals and preferences of academia and industry may not always fully coincide, both parties understand and accept each other's needs and special requirements. Academia, for example, must produce high-quality, peer-reviewed scientific publications ('publish or perish'), while industry must obtain value for the money they invest in research. It is also acknowledged, and with great pleasure, that the vast majority of Finnish companies understand that new products and innovations cannot be achieved in the long run without deeper understanding of the basic mechanisms of material behaviour. This in turn can only be obtained through long-term, systematic, high-quality scientific research.

Another change that has become clear over the past half decade is that companies seldom set limitations on the publication of generic scientific results obtained in research projects. On the contrary, they very often prefer to be active in contributing to publication processes, for example as co-authors. I truly believe companies find this kind of publicity invaluable, strengthening their public and professional image as dynamic and research-oriented players in the tightening international markets. We should also recognise another important factor behind the undeniable success of FIMECC DEMAPP: the tremendous collaboration and work-sharing between the participating research groups. Ad-hoc research networks for tackling specific problems, and use of a wide variety of research facilities and expertise – especially

the latter – have emerged in most projects and sub-projects with apparent effortlessness. For this, I feel, we can thank all the first-class people working in all levels of the programme, and the excellent team spirit that has been simply amazing at all stages of the programme.
The volume of results produced and documented in all projects and subprojects within FIMECC DEMAPP is vast. Researchers will continue writing scientific papers and doctoral thesis manuscripts long after the project on the basis of the results obtained. More importantly, now is the time for the participating companies to go through all the results carefully, both in the projects in which they have been directly involved and across the entire programme, and to exploit them to the fullest extent. Only in this way can the expectations and promises of five years ago of the participating companies, universities and research institutions be fully redeemed!

Veli-Tapani Kuokkala

Professor of Materials Science
Tampere University of Technology

Heavy Metal – from Research to Applications

Over the course of the past decade or so, Ruukki has evolved into a customer-driven steel specialist. The years from 2003 to 2008 were a period of strong demand, growth and excellent profitability, ending in recession triggered by the financial crisis. Since then, we have seen the "new normal", a period of depressed demand, overcapacity and lower growth, especially in the European steel business. It was at this point that Ruukki developed direct quenching, a new technological innovation transforming us into one of the leading manufacturers in abrasion resistance and ultra-high-strength steel.

The FIMECC DEMAPP years from 2009 to 2013 brought expansion in the use of direct quenching, with research work giving rise to new abrasion-resistant and ultra-high-strength structural steel families. Optimisation of process parameters and novel chemical compositions enable excellent combinations of mechanical properties, surface quality, thickness accuracy and, above all, usability in the workshop and for end users.

The background to success has been the intensive co-operation, good basic research and excellent togetherness of the members of FIMECC DEMAPP. The result is a new way of working in which development processes are inclusive of all actions, from basic research through to end use. In the case of Ruukki, for example, the University of Oulu investigated steel microstructure and mechanical properties, Ruukki used these results to develop the steels, Tampere University of Technology tested durability in the field, and METSO Oyj and others clarified the practical application.

FIMECC DEMAPP R&D projects also helped to expand the thickness range of Ruukki's abrasion-resistant steels, bringing about delivery covering 2 mm to 80 mm. Thinner cut-to-length steels down to 2 mm are mainly aimed at lightweight products for improved energy efficiency and lower fuel costs in the transport industry. A typical example is tipper bodies, where Ruukki has develop new concepts in co-operation with customers and end users, one being a half-pipe type body that seeks to take full advantage of the novel possibilities offered by

Raex. Applications for 80-mm thick plate can be found mainly in buckets and mining machines, with thicker Raex grades generally serving the mining industry. Uses including the manufacture of parts for heavy plant and equipment designed for excavation, loading, transporting and crushing ore in mines. Plates up to 80 mm extend the lifespan of mining, construction and recycling applications.

The real impact of the FIMECC DEMAPP programme will be evident soon enough. We shall see it as extended lifespan of machinery, increased wear resistance, and cost savings in various structural components. Most of all, we shall see it in the form of a decreasing ecological footprint. All these will serve to improve Finland's competitiveness in the continuously changing markets of the world.

Jukka Kömi

Director, Product Development, Hot Rolled Steel
Ruukki Metals Oy

PROJECT 1: Wear-resistant Materials and Solutions

The main aim of the project was to enhance the fundamental understanding of wear behaviour and wear mechanisms of new engineering materials in selected application environments, to provide new experimental research techniques and facilities as well as models and methodologies for the simulation of wear phenomÄena under various conditions, and to provide novel materials and coating solutions for the benefit of Finnish industry.

Key outcome: New grades of wear-resistant steels with increased thickness were developed especially for the needs of the excavation and mining industry. New protection steels were also developed, both for civilian and military applications, as well as novel coatings against heavy abrasion. At the moment, the highest international level in wear research is represented by the state-of-the-art wear research infrastructures – both general purpose and application-oriented – and by the new methodologies for multi-scale modelling of the properties and wear performance of materials, including both steels and polymers.

The results of the project had a significant role in selecting materials for a new type of crusher for mining applications. The design of new wear testing devices, the remarkable amount of testing data, and the know-how derived from the results, have educated skilled wear experts both in the universities and research institutes and in the companies. In Metso Corporation, the persons involved in the DEMAPP project have been relocated to new positions in different business lines, making good use of the developed know-how and processing it further.

Metso Oyj

PROJECTS:

- Production and Properties of New Wear-resistant Materials
- Novel Surface Treatments, Coatings and Claddings
- Material Performance and Design Criteria
- Friction and Wear of Polymers

Production and Properties of New Wear-resistant Materials

This subproject was set up to increase understanding of the factors limiting the production and use of steels subjected to abrasive wear, and to use this knowledge to produce and make better use of wear-resistant steels. Both these goals have been well met.

The starting point for the project was the then newly implemented, prize-winning direct-quenching technology at Raahe steelworks. After successful implementation on the hot strip mill early in the millennium, direct quenching was extended to the plate mill just before the start of the project: the aim was radical change in the steelworks' product spectrum to high-added-value, ultra-high-strength steels. Especially in the case of the plate mill, the change was enormous: product strengths tripled!

The main use of the new steels was in abrasion-resistant and protection applications. Abrasion-resistant steels are a niche product in the steel world, but widely used in applications such as excavator buckets, the wearing parts of mining machines, concrete mixing plants and wood processing machines, truck platforms, feeders and funnels. These are all exposed to high abrasive wear, surface pressures and dynamic loading conditions. Protection steels also have high hardness and strength, but in addition they have tested ballistic or blast-resisting properties as required for security vans and military vehicles.

The most cost-effective solutions for the above applications are often martensitic low-alloy steels, heat-treated to high hardness levels in the range 400–500 HB. Traditionally, these steels have been made by reheating hot-rolled plate and water-quenching it to martensite. In the case of Raahe steelworks' direct-quenching process, the water quenching is applied immediately after hot rolling. This saves

capital investment, speeds up production, saves energy and reduces costs. It also improves the surface quality and dimensional accuracy of the abrasion-resistant and protection plates. At the start of the project, therefore, the products had the potential for growth on the export markets and for radically increasing the share of special products made at the steelworks. However, the metallurgy and technology of direct quenching was still in its infancy at the start of the project: to enable an attractive product portfolio to be built, new scientific knowledge was required regarding the factors controlling properties such as toughness and hydrogen-assisted cracking. Only by addressing these issues has it been possible to develop thicker, harder and tougher abrasion-resistant and protection steels and to gain the knowledge necessary for developing still better-performing steels in the future.

Figure 1.
Tipper body, Raex 400. Reduction of weight > 35 % and welding work ≈ 60 %

Figure 2.
Excavator bucket, Raex 500

Figure 3.
Armoured passenger car, Ramor 550

With the help of the R&D work, the maximum thickness of Ruukki's abrasion-resistant steels has been increased from 20 to 80 mm. This has been an essential development for applications such as excavator buckets and mining machines. It has also been possible to improve the quality of the thinnest products down to 2 mm, which is critical in lightweight applications aiming to improve energy efficiency and lower fuel costs in the transport industry, for example.

The highest strength protection steel prior to this project was Ramor 500, but the project research has allowed development of an even stronger grade – Ramor 550. This can be used in civilian and military protection applications such as protected vehicles. The higher strength Ramor 550 enables customers to reduce the thickness needed for ballistic protection, thereby lowering the weight of the vehicle.

Laboratory production of tough 600 HB abrasion-resistant steel successful

A third highlight of the project is the research work laying the foundations for the production of a tough abrasion-resistant steel with a hardness of 600 HB. This has been possible through laboratory exploration of a number of different microstructural approaches, based on 22 chemical compositions and 23 different rolling practices and cooling paths, leading to 90 experimental laboratory strips and 12 full-scale production plates. Laboratory-scale trials have shown that full-scale production should be feasible soon after completion of the project.

PROJECT NAME

P 1 Wear-resistant Materials and Solutions

WSP 1

CONTACT PERSON

PERTTI MIKKONEN
RUUKKI METALS OY

DAVID PORTER
UNIVERSITY OF OULU

PARTICIPANTS (ORGANISATIONS)

RUUKKI METALS OY
UNIVERSITY OF OULU
METSO OYJ

PROJECT DURATION

2009 – 2014

PROJECT VALUE (EUR)

2.002 MILLION

Production and Properties of New Wear-resistant Materials

Main targets & motivation

This project has aimed at obtaining and applying a deep understanding of the relationships between the processing and properties of wear-resistant materials made using two innovative routes to finer microstructures: 1) quenching directly after hot rolling and 2) rapid solidification.

In the case of direct quenching, the aim was to develop abrasion-resistant materials that have unique combinations of properties of use to end users and fabricators, if possible in the form of a wear-resistant steel with a hardness of 600 HB. At the outset of the project, direct quenching as a means of producing wear-resistant steels was largely unknown outside Raahe steelworks. The time, energy and cost savings associated with direct quenching of strong, high-hardness steels had generated much enthusiasm regarding its potential for radically changing the product spectrum of the steelworks to mainly high added value. However, many technical difficulties requiring fundamental metallurgical research stood in the way of its wider application. In the case of the ultra-high-strength, high-hardness steels concerned, the main research problems to be solved fell into two categories: 1) how to improve toughness, and 2) how to prevent quench cracking and delayed cracking in production.

In the case of rapid solidification, the project has been aimed at evaluating the fundamentals and potential of spray forming in the production of special tool steels. Special wear-resistant

materials are needed for advanced wear parts in crushing, recycling and grinding processes. Making them from hard cast steels or cast irons leads to coarse microstructures with low ductility and formability. In spray forming, highly alloyed melt droplets are solidified into finer, more homogeneous, tougher wear-resistant microstructures due to the high cooling rate of the melt.

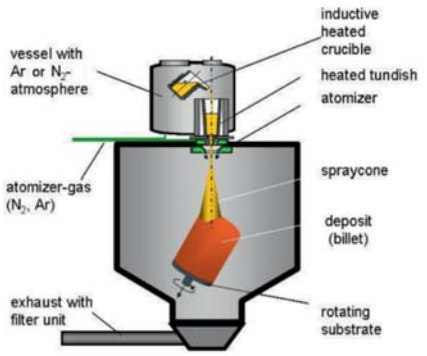


Figure 1. **Spray-forming process**

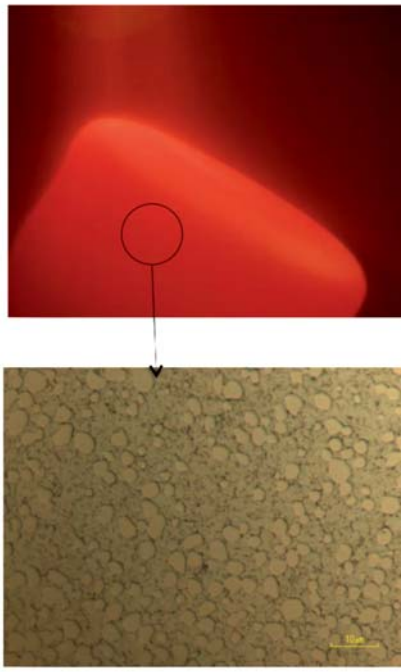


Figure 2. **Microstructure of spray-formed tool steel**

Results

Thermomechanical rolling and direct quenching increase hardness above the theoretical maximum for conventional processing

The effect of chemical composition, hot-rolling parameters and cooling path on the microstructure, hardness, wear resistance and impact toughness of steels in the hardness range 500–700 HB was established. Initial attempts to scale up successful laboratory-scale results based on 0.47% C to production scale proved unsuccessful because the production parameter window was too narrow for consistent achievement of the desired martensitic-bainitic-austenitic-ferritic microstructures. An alternative approach to achieving 600 HB abrasion-resistant grades based on 0.35% C and martensitic-austenitic microstructures, however, proved successful in the laboratory scale (see adjacent figure) and at the end of the project is ready for scaling up to production trials.

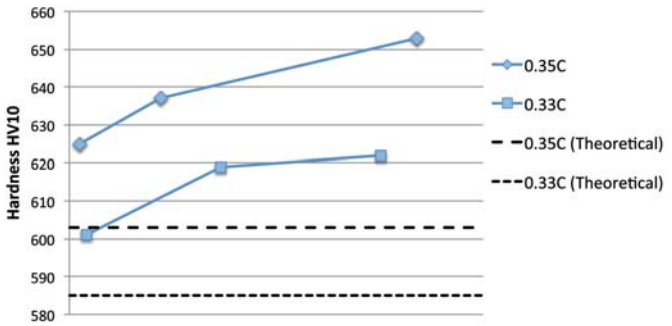


Figure 3. **Increasing rolling reduction below recrystallisation temperature**

The relationship between fracture toughness characteristic temperature T0 and Charpy impact transition temperature T28J for quenched ultra-high-strength steels has been studied and found to be consistently less favourable than for lower-strength steels even after tempering. This is the subject of further research in a follow-on project.

Macrosegregation and semi-macrosegregation were shown to be detrimental to the hardness distributions, toughness and sensitivity to hydrogen-assisted cracking. The completely new understanding of how segregations form and how they are related to casting parameters was critical in enabling the development of the thicker and harder wear-resistant grades described below.

As a result of the fundamental laboratory research it has been possible to widen the thickness range significantly and improve the toughness and weldability of abrasion-resistant steels with hardnesses in the range 400–500 HB: the proprietary grades Raex 400, Raex 450 and Raex 500 can now be produced with excellent toughness and fabrication properties in thicknesses up to 80 mm, which is four times greater than was possible at the start of the programme.

Although the laboratory research has yet to lead to successful full-scale production of 600 HB abrasion-resistant plate, it was possible as a spin-off of the work to develop the protection steel Ramor 550, which has superior ballistic properties to the Ramor 500 that existed at the outset of the programme.

Solving toughness-hardness issues enabled a fourfold increase in the maximum thickness of abrasion-resistant steels

Evaluations of the hot ductility characteristics of spray-formed highly alloyed material provided the knowledge needed to laboratory hot roll the material into test samples for field tests that are still in progress. As a result of the fine dispersion of carbides in the microstructure, the toughness of material was superior to similar cast material. However, higher hardness improved the wear resistance.

Key publications

1. Kinnunen, E., Miettunen, I., Somani, M.C., Porter, D.A., Karjalainen, L.P., Alamattila, I., Kemppainen, A., Liimatainen, T. & Ratia, V. (2013), Development of a New Direct Quenched Abrasion Resistant Steel, International Journal of Metallurgical Engineering, Vol. 2 No. 1, pp. 27–34.
2. Ratia, V., Miettunen, I. & Kuokkala, V-T. (2013), Surface deformation of steels in impact abrasion: The effect of sample angle and test duration, Wear, Vol. 301, Issues 1–2, April-May, pp. 94–101.
3. Kaijalainen, A., Pallaspuro, S. & Porter, D.A. (2014), Tempering of Direct Quenched Low-Alloy Ultra-High-Strength Steel, Part I – Microstructure, Advanced Materials Research Vol. 922, pp 316–321, Trans Tech Publications, Switzerland, doi:10.4028/www.scientific.net/AMR.922.316.
4. Pallaspuro, S., Kaijalainen, A., Limnell, T. & Porter, D. (2014), Tempering of Direct Quenched Low-Alloy Ultra-High-Strength Steel, Part II - Mechanical Properties, Advanced Materials Research Vol. 922 (2014) pp. 580–585, Trans Tech Publications, Switzerland, doi:10.4028/www.scientific.net/AMR.922.580.
5. Pikkarainen, T.P., Vuorenmaa, V.V., Rentola, I.A., Leinonen, M.J. & Porter, D.A. (2014), Effect of superheat on macrostructure and macrosegregation in continuous cast low-alloy steel slabs. Institute of Physics Conference Series: Materials Science and Engineering (MSE) (submitted).

Number of publications: 5
Number of Master's Theses: 5
Number of patent applications/patents: 1

Networks and international co-operation

Metallurgical studies and usability tests have been made in co-operation with Finnish Universities, Research Centres and Ruukki Metals. The researchers at the Centre of Advanced Steels Research at the University of Oulu (CASR) have studied the microstructure and thermomechanical hot rolling using Gleeble thermomechanical simulators and laboratory rolling experiments. At the Tampere Wear Center at the Tampere University of Technology (TWC), researchers have studied the wear behaviour and usability of the steels. The behaviour of protection steels at ultra-high strain rates was studied using a Hopkinson Split Bar (HSB) facility. METSO Oyj clarified the usability of the steels and their practical applications. Use has also been made of progress

in the FIMECC programmes LIGHT and ELEMET, which have served as both sources and recipients of the new ideas, and increased the understanding needed for successful development of the above abrasion-resistant and protection steels. Internationally, co-operation with Prof. R. Devesh K. Misra at the Center for Structural & Functional Materials of the University of Louisiana at Lafayette, USA, enabled evaluations of retained austenite morphologies to be made using transmission electron microscopy. The University of Bremen supplied the spray-formed material.

Applications & impact

The expanded thickness range of the Raex abrasion-resistant steels up to 80 mm has been pivotal in widening the application of the steels in the mining industry, e.g. in the manufacture of equipment for excavation, loading, transporting and crushing of ores. In other heavy plant applications too, such as construction and recycling, thick plates help extend component lifespan.

The development of thinner Raex grades in thicknesses down to 2 mm has widened application of the steels in energy-efficiency solutions in the transport industry. A typical example is tipper bodies, where Ruukki has developed new concepts in co-operation with customers and end users. One of these was a half-pipe type body that makes use of the improved properties resulting from the project.

By using the newly developed Ramor 550 steel in place of Ramor 500, the customer can reduce the thickness needed for ballistic protection, thereby decreasing for example the weight of the protected vehicle in civilian or military protection applications.

Breakthrough protection steel developed

Taking into account availability issues and production costs, spray-formed highly alloyed tool steels, with their significantly improved mechanical and wear properties, will be good candidates for advanced wear parts in particularly aggressive wear environments. The new material developed has been produced in industrial scale and will be tested in several applications in mining and crushing equipment. The alloy development will be continued.

Novel Surface Treatments, Coatings and Claddings

Evaluation of wear performance of fibre refinery blades in a simulator and testing facility

A unit for testing fibre refinery blade wear was installed in the Department of Materials Science at Tampere University of Technology. The equipment is suitable for testing materials with abrasive particles, simulating the real environment in which they are used. Use of this equipment enables the development of new materials and coatings for the pulping industry with greater wear- and corrosion-resistance. A Master of Science thesis was conducted, using the equipment for testing several kinds of cast blade materials within the framework of WSP 2 of the DEMAPP Research Programme.

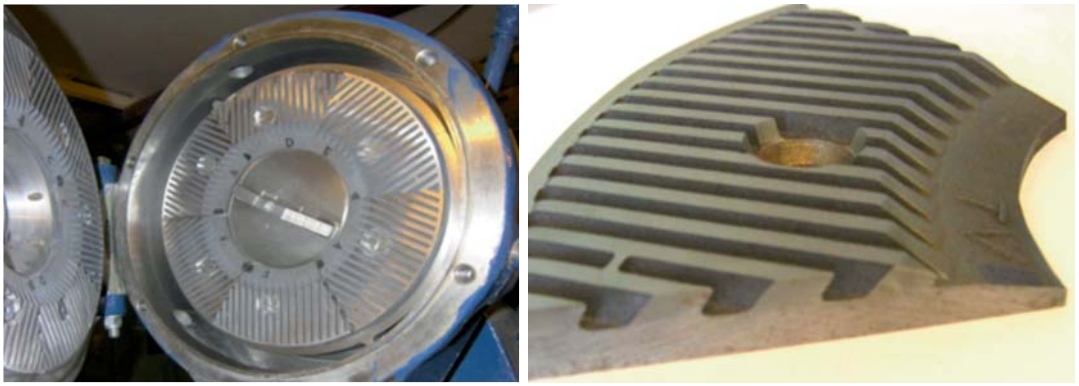


Figure 1. **Opened testing unit and a fibre refinery blade to be tested**

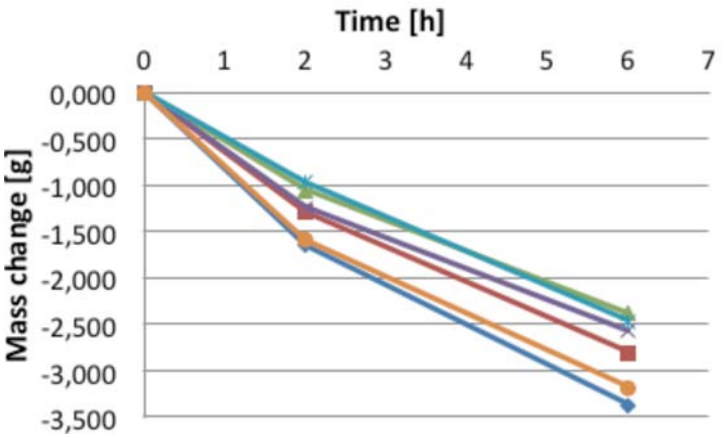


Figure 2. **Mass change of the rotor blades during the test procedure**

Formation and structure of WC-CoCr HVAF coating on a steel surface with different spray angles

Thick and dense wear-resistant coatings by thermal spraying

The high-velocity air fuel thermal spray method (HVAF) is used to produce thick and dense high-quality abrasion-resistant coatings. The method is productive and cost-effective when used to coat considerably large surface areas. In normal production, the surfaces to be coated are often angular and complicated in shape, which makes it necessary to form the coating with different coating angles. In the present work, the HVAF method was used to manufacture WC-CoCr coatings on mild steel substrate with deposition angles between 0 and 90 degrees.

This work evaluated the structure of the coating and measured coating thickness using optical and scanning electron microscopy. The hardness of the coating was measured using a micro hardness tester with 300 g or lower loads.

The microstructure of the coating was found to be considerably dense, even with relatively low spray angles. The coating was also made up with very low or even near 0 degrees spray angles. The porosity of the coating remained at tolerable levels, in spite of the use of oblique spray angles in coating manufacture.

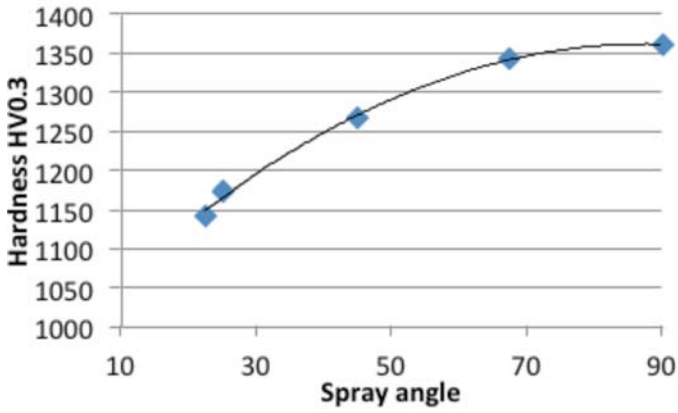


Figure 3. **Hardness HV0.3 of the coating as a function of the spray angle**

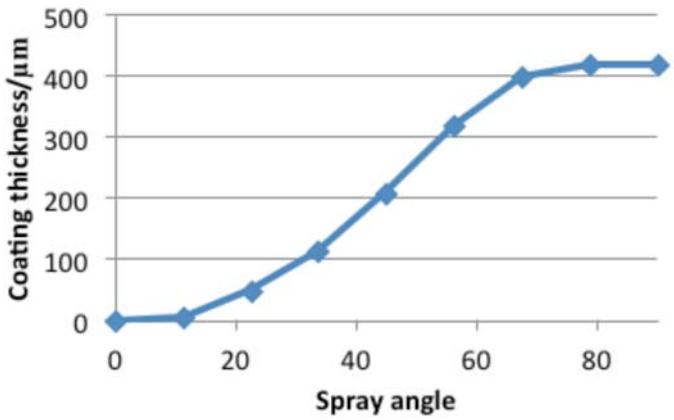


Figure 4. **Coating thickness as a function of the spray angle**

Microstructure and wear behaviour of vanadium-carbide-reinforced weld coatings

High resistivity against hard abrasive wear conditions can be obtained by coating the bulk low-cost base material with high-performance-tool steel coating. In this study, thick wear-resistant coatings of vanadium-carbide-reinforced tool steel were manufactured with a conventional plasma-transferred arc-welding or cladding (PTA) technique. Two different coated test piece configurations were prepared for wear tests and microstructure characterisation work. The coatings were heat treated in temperatures at or well over the austenising temperature of the steel base material used. The state of the coating

materials was characterised with hardness measurements, cross-sectional microstructure studies with scanning electron microscopy, and X-ray diffraction measurements. Abrasive wear resistance of the heat-treated coatings was evaluated with a modified ASTM G65 rubber wheel abrasion wear test, while special impact wear tests were used to test impact resistance in very severe wear conditions. Heat treating after the welding procedure is seen to be very effective in removing the retained austenite from the coating material structure, and to produce very fine detailed precipitate structure besides more coarse V_4C_3 carbides in the coating material. Abrasive wear resistance of the tested coating material was found to be low against hard silicon oxide particles used in the tests. This is mainly because of the small carbide size, and also the low volume fraction of these carbides reinforcing the coating material against abrasive wear. Heat treatment over 950ºC was hardening the coating, and use of higher heat-treating temperatures therefore found to be reducing the impact wear resistance of the coating. This was because particles were fracturing off the sharp test piece edge during the test.

Characterisation of impact wear resistance of advanced coating materials plays a key role in manufacture of high-performance tools

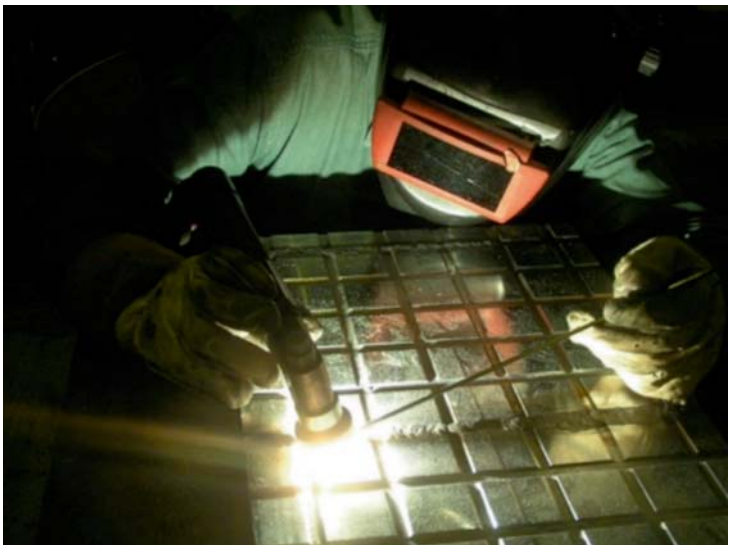
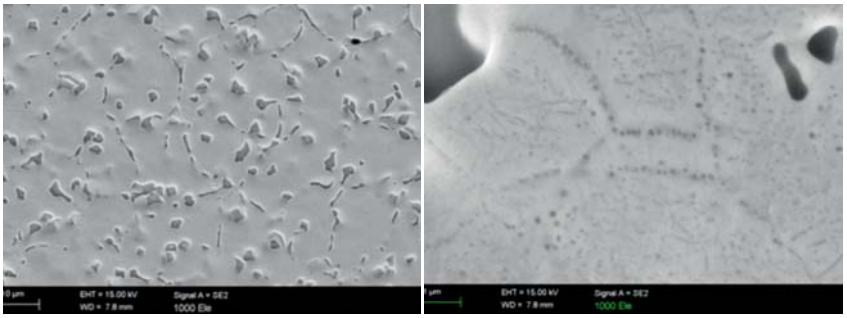


Figure 5. **Welding of wear-resistant cladding**



a) b)

Figure 6. **a) Cross-section of heat-treated PTA-weld vanadium-carbide-containing tool steel coating. b) Electro-polished cross-section of heat-treated PTA-weld vanadium carbide coatings on tool steel. The figure is taken from single bead specimens prepared for impact tests and X-ray diffraction studies. Note the fine detailed precipitate structure inside the grains and on the grain boundaries**

PROJECT NAME

P 1 Wear-resistant Materials and Solutions

WSP2

CONTACT PERSON

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METSO MATERIALS TECHNOLOGY
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PROJECT DURATION

2009 – 2014

PROJECT VALUE (EUR)

0.539 MILLION

Novel Surface Treatments, Coatings and Claddings

Main targets & motivation

The aim of the project was to screen, select and study the properties and manufacturing methods and further develop new surface treatments and coatings in co-operation with the WSP 3 project. The second objective was the understanding of structural stability, together with impact and compressive wear behaviour of surface-treated components.

The research work in WSP 2 focused on studying and developing essentially thick wear-resistant coatings and other surface layers. These are expected to solve the challenges of highly demanding industrial applications after several years of fundamental research, although some thinner surface treatments and coatings were also included in the study. The new surface treatment methods were brought to be further developed for Metso (Valmet) applications.

Other objectives were to understand the structural behaviour of surface-treated components by impact and compressive abrasive wear, to develop and screen novel protective coatings for different highly demanding wear environments, and to understand the effect of processing parameters and coating material properties on wear phenomena in order to be able to tailor the coating properties. A further aim is to understand the effect of wear-resistant surface treatments on the mechanical properties of components.

Results

Modern high-velocity thermal spray methods give good coating quality on complex shaped surfaces

- New information about the structure and impact resistance of PTA-coated structures for heavy abrasive wear applications
- Demonstration and evaluation of novel highly wear-resistant coatings made by HVAF thermal spray technique on complex substrates
- New information about the surface behaviour of chromium-containing steel products during diffusion treatments

Key publications

1. Laurila, J. et al. (2013), Microstructure and wear behaviour of a vanadium carbide reinforced weld coating, Wear, Vol. 307, pp. 142–149.
2. Laurila, J. et al. (2012), Dynamic Corrosion and Wear Testing of Corrosion Resistant Thermal Spray Coatings and Wrought Reference Material in Chlorine-containing Conditions with Low pH Values, In: Lima, R.S. et al. (ed.). Thermal Spray 2012. Proceedings from the International Thermal Spray Conference and Exposition, Houston, Texas, USA, pp. 76–80.
3. Laurila, J. et al. (2013), Abrasion wear and corrosion resistance in chlorine-containing conditions of iron-based thermal spray coatings. Thermal Spray 2013: Proceedings from the International Thermal Spray Conference and Exposition, Busan, South Korea.
4. Laurila, J. et al. (2014), Formation and structure of WC-CoCr HVAF coating on steel surface with different spray angles. In 28th International Conference on Surface Modification Technologies, 16–18 June, Tampere, Finland.

Number of publications: 6
Number of Master's Theses: 1
Number of Bachelor's Theses: 2

Networks and international co-operation

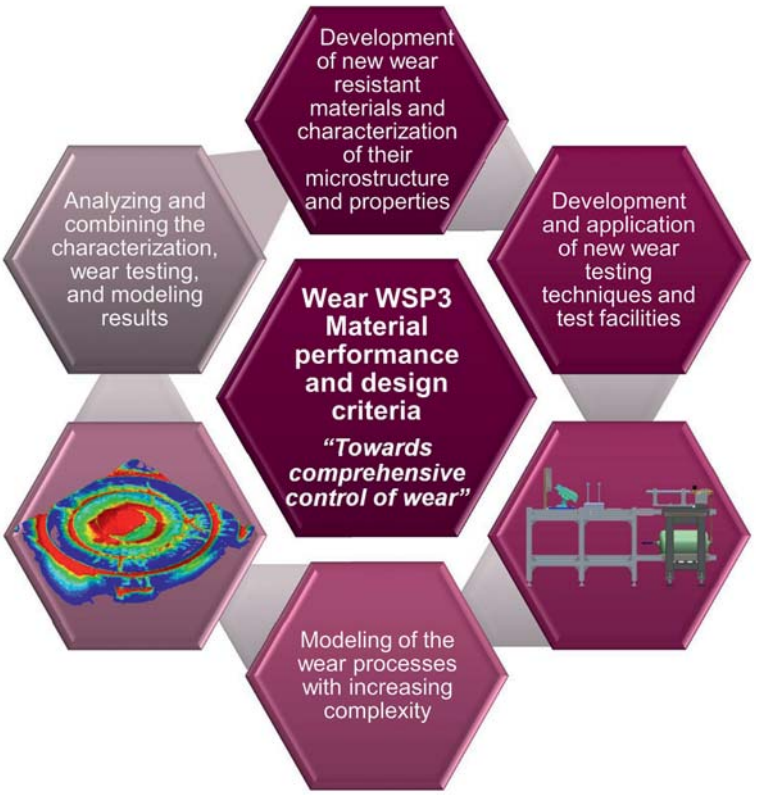
Special wood grinding blades for further wear testing were prepared together with Expanite in Denmark. Part of the composite blade test runs was performed at Åbo Akademi University. Co-operation/research exchange being conducted in this field concentrated mainly on thermal spray coatings but, with associate professor Luca Lusvarghi and his research group at the University of Modena Reggio (UNIMORE) in Italy, also on welded thick coatings. PhD student Andrea Milanti was also in Tampere until the end of the project, partly working with this subject while preparing his doctoral thesis on iron-based wear and corrosion-resistant coatings using HVOF and HVAF spray technologies.

Applications & impact

Surface modification of constructions gives new value to the final product

- Wear and impact testing achieved new information about abrasion, and especially impact wear resistance for modern applications of tool steel claddings. Collection and establishment of the correlation of the microstructure, properties and wear performance of these materials.
- A unit for testing fibre refinery blade wear was installed in the Department of Materials Science at Tampere University of Technology. The equipment is suitable for testing materials with abrasive particles, simulating the real environment in which they are used.
- Better understanding achieved of the surface modification treatments of corrosion-resistant steels, and characterisation of the value of these treatments for further use in industrial processes.

Material Performance and Design Criteria



Wear in its various forms is a common cause of material failures, frequent replacement of parts and components, general loss of productivity, and indirect energy losses and increased environmental burden. Improvements and new innovations in the wear resistance of materials will have a great impact on the energy and cost-efficiency, environmental issues, and safety requirements increasingly faced by industry. The experimental research plays a key role in solving various practical wear problems

Four novel wear-test devices developed simulating actual wear conditions

and, especially, in enhancing scientific understanding of wear phenomena and wear mechanisms. The following four novel wear-test devices were developed in the project: a dual pivoted laboratory jaw crusher, an impeller-tumbler impact-abrasion tester, a high-speed slurry-pot tester, and a high velocity particle impactor (HVPI) for wear model and simulation validation. The test devices were designed to simulate wear systems in typical end-user applications for wear-resistant steels.

While the standard laboratory jaw crusher has a fixed opening angle and fixed movement between the jaws, the **novel dual-pivoted laboratory jaw crusher** can be used to determine the material properties beneficial to wear resistance in any combination of compressive and sliding abrasion. The dual-pivoted jaw crusher also facilitates measuring of the work (energy) in comminutive processes and enables assessment of the abrasiveness and crushability of minerals. The results of these tests have already provided invaluable data for modelling and understanding the wear behaviour and wear mechanisms in abrasive crushing environments.

In the industry, the test device and the accumulating data and knowledge can be used, for example, in process planning and development of process optimisation tools for companies such as Metso Minerals and Ruukki Metals who deal with the crushing, processing or moving of natural rock.

The abrasive, impact-abrasive, and impact-wear behaviour of numerous commercial and experimental grades of wear-resistant direct-quenched steels, manganese steels, tool steels, and metal matrix composites were tested at TWC and AC2T. Ruukki's direct-quenched steels had different microstructures obtained by varying the alloying and quenching parameters. In all tests, higher hardness led to decreased mass loss, but in impact abrasion the hardness dependence was smaller than in the high-stress abrasion tests. Thus, it is essential that the contact conditions and the whole wear environment are properly taken into account when determining the wear performance of materials. It was also **verified that hardness alone is not an accurate predictor of the steel's wear performance**. The alloying and manufacturing of the steel, and thus its microstructure and hardness profile, also has a significant effect, particularly on the work-hardening and mechanical behaviour of the steel during abrasion and impact, leading to different wear performances under such conditions. When testing the abrasive wear performance of 15 commercially available 400 HB grade quenched wear-resistant steels from all over the world, differences of over 50 per cent were recorded. As abrasive wear covers

about two thirds of industrial wear problems, this kind of a comparative study is of significant practical importance. The results can be used, for example, in various mining and mineral processing applications.

The structures of ballistic shields largely depend on the expected threats. The focus in this project was on Ruukki's direct-quenched steels and their shield properties against projectiles. Experimental ballistic tests (STANAG) were simulated and parameters achieved for the material models of Ramor 500 steel. This means that different shield structures made from Ramor steel can now be verified by simulations, and expensive experimental work minimised. **The Ramor 550 protection steel developed in the project** is intended for customers who seek extreme protection and safety performance for their end products, such as blast protection or high ballistic resistance of cars, security vans, and military vehicles.

Experimental research plays a key role in solving wear problems

The **high-velocity particle impactor** was designed to produce single and multiple impacts of solid particles on different types of materials in order to identify the basic mechanisms influencing the impact wear and failure behaviour of materials. The wear performance and deformation and damage mechanisms of the high-strength steels provided by Ruukki and Metso were experimentally determined with the HVPI test setup at various angles and impact energies. All the steels studied exhibited greater wear and plastic deformation at high impact angles. The high-rate deformation behaviour determined with the Hopkinson Split Bar testing systems and the microstructural features identified with the EBSD technique were implemented in the multi-scale simulation models. The connection between localised crystal plasticity and the strain hardening behavior of various steels was studied to further develop the material models. In addition to impact wear, the high stress abrasive conditions were physically simulated with single and multiple scratch tests at various loads to investigate the effect of strain hardening and wear behavior of different microstructures. In the tests, all parameters and variables were strictly controlled to make them suitable for the verification of the numerical simulation models. Thus, exactly the same experiments could be done both physically and numerically.

Microstructure-based multiscale modelling was used to investigate the wear behaviour of high-strength steels and metal matrix composites. The **multiscale modelling and simulation approach** enables the establishment of links between material microstructure and its properties, microstructure and wear performance, and production of methods for understanding and quantifying the conditions to which the materials are subjected in component- and process-loading condi-

tions and environments. Transferability of small-scale experimental data to component scale can also be addressed, and design of appropriate material solutions improved in a case-specific and tailored manner.

Impact and abrasive wear processes were modelled computationally during the course of the work. As a result, a toolset was developed for tailoring materials and performing component design for such wear-inducing conditions. The main exploitation pathway is the establishing of links and correlations between wear-inducing conditions, micromechanisms of wear and material microstructure. Simulations can be carried out to study any such particular features in detail, as well as to carry out "what-if"-like scenarios and sensitivity analyses, e.g. related to the significance of specific characteristics of material microstructure.

Multiscale modelling links the microstructure to wear performance

The multiscale modelling methodology was developed and applied for five different materials, ranging **from wear-resistant steels to metal matrix composites and thick wear-resistant coatings.** For high-strength steels, the significance and role of martensite sub-structures was investigated, and specific prior austenite grain sub-block structures demonstrated to be of great significance for wear resistance, with respect both to their morphology and to orientation distribution. For metal matrix composites and coated systems, the tailoring of their microstructural carbide structures was found to be an exploitable route to addressing and tailoring wear resistance in a case-specific manner. Various studies of the fundamentals of wear micromechanisms were carried out, such as the study of shear-slip localisation in high-strength steels as a result of high-rate deformation and impact-wear conditions. A key feature of the simulation workflows was consistent linkage to experimental and characterisation activities, to yield consistent validation and verification as well as produce models with predictive capabilities.

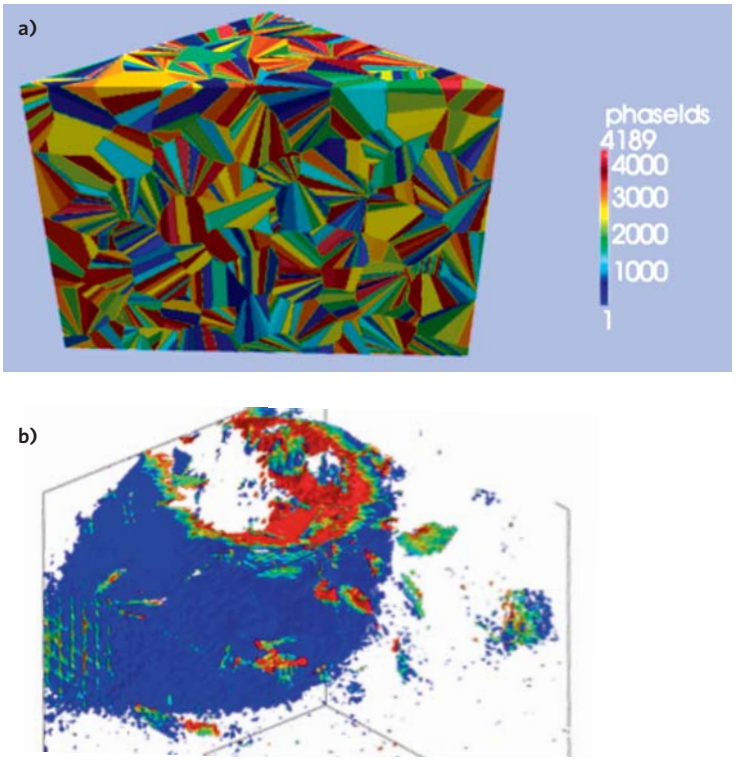


Figure 1. **Examples of a) computational martensite block structure and b) multiscale finite element model for analysing microstructural response during an HVPI experiment**

Figure 2. **New wear test devices and procedures narrow the gap between research and practice**

PROJECT NAME

P 1 Wear-resistant Materials and Solutions

WSP3

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METSO OYJ
RUUKKI METALS OY

PROJECT DURATION

2009 – 2014

PROJECT VALUE (EUR)

5.361 MILLION

Material Performance and Design Criteria

Main targets & motivation

Abrasive wear causes huge expenses and environmental burden

Wear is one of the most common mechanisms causing damage and failure of materials and components. In spite of this, the control and theoretical understanding of wear clearly lags behind the progress made in other fields of materials science and technology. The main reason for this is evidently that wear, rather than being a single phenomenon, is a large collection of various mechanisms, processes, and environmental conditions. It should also be emphasised that there is no such generic material property as 'wear resistance', which would describe the material's general performance in wear-prone applications. For these reasons, experimental research plays a key role in solving various practical wear problems and, especially, in enhancing scientific understanding of the wear phenomena and wear mechanisms. Experimental work is further needed to generate reliable material data for the models used in the simulations, and to verify and validate the simulation results.

An open wear-research environment with special wear-research facilities enabling long-term high-quality research and national and international networking was one of the main targets of WSP 3. The specific objectives of the project were the enhancement of the fundamental understanding of heavy abrasive and impact wear of new engineering materials and better understanding of the role of various wear mechanisms in selected wear environments. Moreover, an important part of the project was to provide new models and methodologies for the simulation of wear phenomena under various conditions.

Results

- Most of the defined targets were reached or exceeded from both industrial and academic perspectives. The main results of the project can be grouped under the following three categories or highlights: 1) Development of general purpose and application-oriented wear research infrastructure, 2) Enhancement of the understanding of wear mechanisms in selected wear environments and development of new wear-resistant steels and coatings, 3) Correlation of the microstructure, properties and wear performance of materials through multiscale modelling.

New wear test devices narrow the gap between research and practice

- Both general purpose and application-oriented wear research infrastructure was developed in the project. New test devices and test environments designed and constructed in the project include, for example, a dual-pivoted laboratory jaw crusher, an impeller-tumbler impact-abrasion tester, a high-speed slurry-pot tester, and a high-velocity particle impactor (HVPI) for wear model and simulation validation.
- The jaw crusher test results help to understand which material properties are beneficial in different wear environments. The energy spent in comminution and the abrasiveness of the rock, on the other hand, are important factors in the process planning of companies dealing with crushing, handling or moving of natural rock.
- Better understanding of the wear phenomena has enabled the development of new steels with improved wear resistance. In addition to hardness, the alloying and manufacturing of the steel, and thus its microstructure, has a significant effect on work-hardening and mechanical behaviour during abrasion, leading to different wear performances under high-stress abrasive conditions.
- Multiscale modelling methods were developed during the course of the project in order to establish quantitative correlations between material microstructure, properties and, in particular, the resulting wear performance. The resulting modelling methods enable the simulation of abrasive and impact wear mechanisms using material microstructure as a starting point, and as such enable the study of wear process fundamentals as well as material features dominating the affiliated material performance.

Key publications

1. Ratia, V., Miettunen, I. & Kuokkala, V-T. (2013), Surface deformation of steels in impact abrasion: The effect of sample angle and test duration. Wear, Vol. 301 (1–2), pp. 94–101.
2. Ojala, N., Valtonen, K., Kivikytö-Reponen, P., Vuorinen, P., Siitonen, P. & Kuokkala, V-T. (2014), Effect of test parameters on large particle high-speed slurry erosion testing, Tribology – Materials, Surfaces & Interfaces, Vol. 8 (2), pp. 98–104.
3. Terva, J., Teeri, T., Kuokkala, V-T., Siitonen, P. & Liimatainen, J. (2009), Abrasive wear of steel against gravel with different rock-steel combinations. Wear, Vol. 267 (11), pp. 1821–1831.
4. Lindroos, M., Apostol, M., Kuokkala, V-T., Laukkanen, A., Valtonen, K., Holmberg, K. & Oja, O. (2014), Experimental study on the behaviour of wear-resistant steels under high-velocity single particle impacts. Submitted to the International Journal of Impact Engineering.
5. Ojala, N., Valtonen K., Heino V., Kallio M., Aaltonen J., Siitonen P. & Kuokkala, V.-T. (2014), Effects of composition and microstructure on abrasive wear performance of quenched wear resistant steels. Wear, Vol. 317(1–2), pp. 225–232.

Number of publications: 47
Number of Doctoral Theses: 2
Number of Master's Theses: 3
Number of Bachelor's Theses: 7
Number of invention disclosures: 1

Networks and international co-operation

In the course of the project, research collaboration and researcher exchange was conducted with the National Research Council (NRC) of Canada, the University of Sheffield in the UK, and the Austrian Excellence Centre for Tribology (AC2T, Research GmbH). Also, the Nordic Hard Rock Tribology Network, RockTrib was formed to support Nordic collaboration within the area of mining, drilling and rock excavation, with emphasis on hard rock tribology. RockTrib embraces several key research institutes, including NTNU, SINTEF, Luleå University of Technology, Uppsala University, Dalarna University, Tampere University of Technology and VTT Technical Research Centre of Finland. The wear research infrastructure that was developed further facilitated the international collaboration, and was also used in the other subprojects of WEAR and in the FIMECC LIGHT programme.

Applications & impact

- The test results have been used in the steel development work at Ruukki Metals. For example, steel compositions and process parameters have been optimised to obtain the desired microstructures and mechanical properties. During the DEMAPP programme, the thickness range of the direct-quenched Raex steels was expanded up to 80 mm and down to 2 mm (see also WSP 1). The consequent enhanced understanding of the wear phenomena was the enabling factor in improvement of the wear resistance of the new steels. The results from the wear tests have also been used in customer care, advising customers to select the best materials for their applications. Development of steels with increasingly better wear resistance and at the same time better workshop properties will continue in the FIMECC BSA programme.

Novel Ramor 550 protection steel with excellent ballistic properties

- The Ramor 550 protection steel developed in the project has excellent ballistic properties, in combination with high levels of hardness and strength. Ramor is intended for customers who seek extreme protection and safety performance for their end products.
- A wide range of wear-resistant steels and other novel materials developed in the project were wear tested as prospective materials for Metso's crushing and grinding systems. Several corporate-level research projects were initiated on the basis of these results.
- The dual-pivoted jaw crusher that was developed has proven a valuable tool for better understanding of the combined effects of different crushing parameters and mineral properties. The device and accumulating data and knowledge will be used, for example, in process planning and development of process optimisation tools.

Wear modelling of elastomers – better material solutions developed faster

Friction and Wear of Polymers

Wear modelling and material testing of elastomers

Global demand for material efficiency increases the need for practical understanding of material wear behaviour. Wear control and process optimisation are important steps to sustainable development. Consequently, the attempts to improve and model the processes that have wear challenges cause beneficial effects on resource efficiency. Increasing component lifetime by a factor of three will decrease the demand on raw materials to one third within the same period of time. Elastomer material products, such as material handling hoses, mill liners, screen panels and pump liners, are key components in increasing material efficiency.

The Friction and Wear of Polymers project concentrated on wear modelling and material testing of elastomers. The material data for modelling was collected using dynamic mechnacal analysis (DMA), as well as through tensile, compression and shear testing at different strain rates. Scratch testing and high-velocity particle impactor tests were used for the verification of the models. Various wear tests, such as dry erosion and slurry erosion tests, also increased understanding of the material behaviour and wear mechanisms of various rubber materials under erosive environments. The general target of the project was to develop a suitable and reliable modelling method for estimation and extension of elastomer lifetime.

Wear modelling of elastomers is not well known, because of the complexity of the behaviour of elastomers, e.g. rubbers. Modelling enables a more thorough and deeper understanding of wear phenomena. Improved material solutions and speeding up of the product design cycle can only be guaranteed, however, through comprehending the underlying mechanisms. This also decreases the experimental laboratory testing time and improves accuracy in exploiting the results. Novel modelling methods can gradually be applied in a modelling-assisted material design process to couple the material nano-microstructure and composition to the performance of a component.

Multiscale material modelling is also the only scientifically sound way of predicting the lifetime of materials that become subject to heavy wear. For a wear problem, this can contain finite and discrete element means that enable computational analysis of material behaviour in process environments. Modelling of elastomer behaviour at such accuracy is nonetheless a very demanding task. Modelling relies on the experimental testing of actual rubber material mechanical properties and failure, and on wear models of material behaviour under impact-type surface attacks and erosive environments. VTT Technical Research Centre of Finland has developed and offers solid experience, and advanced computational tools, VTT ProperTune™, to tackle even the most complex material design challenges.

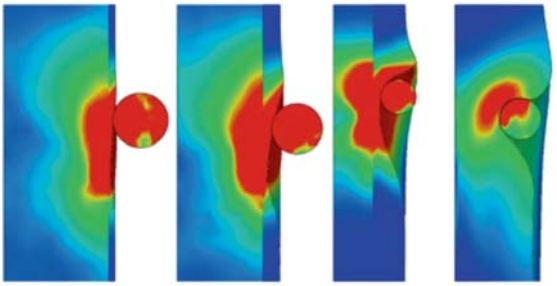

Figure 1. **Modelled single impact with several rubber thicknesses on the substrate material (different colours indicate different stress levels)**

The constitutive model developed for the elastomer material comprises hyperelastic and viscoelastic contributions. The material model is normally calibrated by fitting a single material point model to the experimental results. The experimental results for hyperelasticity consist of tensile, compression and shear tests at different strain rates. Viscoelasticity is determined from creep tests by using the determined creep curves and dynamic mechanical testing. The tensile, compression and shear tests are conducted using servohydraulic material testing machines. The dynamic mechanical analysis (DMA) can be carried out with the dynamic mechanical analyser, which is most reliable in the shear mode, to obtain frequency-dependent viscoelastic material parameters, such as storage and loss modulus values, also as a function of temperature.

The material can be subjected to several different kinds of conditions during its service. More than one type of testing with various conditions and parameters is therefore needed to assess the wear properties of materials. It is reasonable to conduct the model verification using several performance-testing devices in laboratory con-

ditions, such as scratching and sliding conditions, impacting and erosive conditions, and severe abrasive conditions. At Tampere Wear Center, several devices have been designed to simulate actual wear conditions, especially in the field of heavy abrasive and impact wear.

Model verification is done through single-scratch testing of the experimental rubber surface. Penetration depth dependence on the applied force in the scratch testing of rubber materials simulates the hard particle influence in the industrial slurries, and the effect on the rubber liner surfaces. The penetration depth is measured during the scratch test, and a post scan can be carried out for measuring the residual depth.

The high-velocity particle impactor (HVPI) at the Tampere Wear Center is used to conduct impact tests where the experimental parameters, such as the shape and size of the impacting particle and its velocity and impact angle, are strictly controlled. The HVPI data is used to verify and calibrate the numerical simulations based on the high-speed video recording. The device is capable of shooting 9-mm projectiles of different shape and composition at a fixed target at velocities ranging from 30 to 200 m/s.

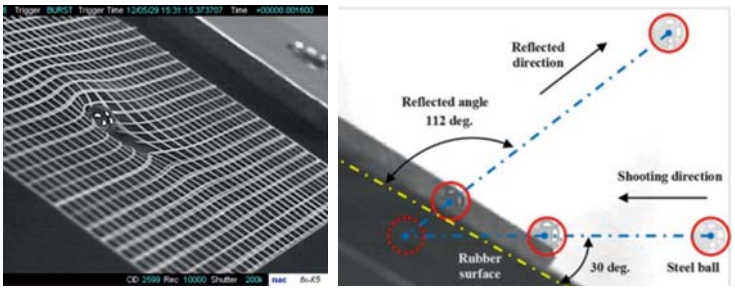

Figure 2. **High-speed video frames of the HVPI tests for rubber**

The HVPI equipment was also used to study the impact properties of stainless steel/rubber/composite hybrid structures. This novel hybrid structure combines low weight (composite) and good corrosion and wear resistance (stainless steel). Due to the adhesive (rubber) it also has additional beneficial properties, such as a very simple manufacturing process and improved dynamic properties. The studies showed that the rubber improves the damage tolerance of the hybrid significantly when compared to a corresponding glued structure. The strongest effect on the behaviour of the hybrid structure was found to be the normal component of the projectile's energy and the rubber thickness. The results are described in detail in Key publications 1 and 2. The results of this study emphasise that the stainless steel/rubber/composite hybrid structure has the potential to replace all-metal components in industrial shell structures, such as engine covers.

Stainless steel/ rubber/composite hybrid structure to replace all-metal components

PROJECT NAME

P 1 Wear-resistant Materials and Solutions

WSP4

CONTACT PERSON
MIRVA MUSTAKANGAS, TEKNIKUM OY
PÄIVI KIVIKYTÖ-REPONEN VTT TECHNICAL RESEARCH CENTRE OF FINLAND

PARTICIPANTS (ORGANISATIONS)
TEKNIKUM OY
METSO MINERALS OY
TAMPERE UNIVERSITY OF TECHNOLOGY
VTT TECHNICAL RESEARCH CENTRE OF FINLAND

PROJECT DURATION
2009 – 2014

PROJECT VALUE (EUR)
1.369 MILLION

Friction and Wear of Polymers

Main targets & motivation

- The objective of the project was to develop and use a model for elastomer wear behaviour in demanding conditions.
- The industry-driven objective was to increase the understanding of the friction and wear behaviour of elastomers and polymers, and the interaction between different materials, loading and environmental parameters in demanding tribological applications in erosive, abrasive, impact and sliding wear contacts. The aim is to provide a clear advantage for the companies in launching high-quality, cost-efficient and environmentally safe products to the market in a reasonable time.

Background

The importance of material modelling have been increased in modern society, there are huge modelling activities going on, for instance:

- The USA has launched the 'materials genome' initiative to reduce the development time of novel materials.(www.white-house.gov/administration/eop/ostp/initiatives#Science)
- In Sweden material modelling is carried out in the hero-m centre (http://www.hero-m.mse.kth.se/), where industrially relevant materials are designed in an integrated process involving all appropriate scales of length and time. The performance of these materials is further tuned to obtain the desired properties at minimum cost and time through a multi-length scale engineering approach.
- In this study, a systematic modelling approach of material performance enables the development and optimisation of elastomer materials for various harsh industrial applications.

- The state of the art in modelling potential for solving industrial problems is in active development, and accelerating with the computer capacity increase. The modelling was developed further than expected during the project because of the rapid development of programmes and hardware.
- The importance of polymers as wear-resistant materials has been growing all the time. Polymers are light in weight, and often relatively cheap compared with traditional wear-resistant materials, such as wear-resistant steels and ceramics. Wear mechanisms of polymers are typically different from steels and ceramics. For polymers, especially elastomers, wear resistance is partly based on the elasticity of the material. Surface friction can also vary considerably within the same material group. The wear behaviour must first be more deeply understood before identifying the kind of applications best suited to polymers.
- Wear-resistant polymers are used in many applications, allowing the results of this project to be widely exploited. The number of different polymers is huge. Polymers are more sensitive to the right circumstances and applications than, for example, metals. Rubbers are typically used in applications where temperature is below 120 ^{0}C. Typically, wear-resistant rubbers perform well in applications where the material is hit by particles, or where the material's friction and wear resistance must both be high. Typical applications are sludge- or slurry-handling applications, such as material-handling hoses, different kinds of liners in pumps, pipes or valve liners, mill liners or other wear elements where rubber is also often used because of its excellent noise and vibration damping properties. Wear-resistant thermoplastics are typically used in different kinds of sliding applications, where low friction and high wear resistance are needed at the same time.

Results

- A methodology for building up the model and finding out the relevant experimental testing procedures for elastomers in specific conditions.
- Building up relevant testing methods suitable for elastomeric materials and facilitating wear ranking of relevant elastomeric materials used for commercial purposes.
- The mechanical properties of several rubber materials were determined by comprehensive mechanical testing.
- A high-velocity particle impactor (HVPI) was developed at Tampere Wear Center in collaboration with the WSP 3 project

to conduct impact tests and to verify and calibrate the numerical simulations. The HVPI tests revealed the marked effect of rubber thickness on impact behaviour.

- The HVPI equipment was also used to study the impact properties of stainless steel/rubber/composite hybrid structures.
- The strongest effect on the induced damage and energy absorbed by the hybrid structure was found to be the normal component of the projectile's energy. Higher rubber thickness also led to less damage. The results emphasise that the stainless steel/rubber/composite hybrid structure has potential to replace all-metal components in industrial shell structures, such as engine covers.
- Erosion tests showed that low impact angles are highly erosive, causing cutting of the studied materials.
- A novel high-speed slurry-pot device was developed at Tampere Wear Center in collaboration with the WSP 3 project.
- A slurry erosion test device was constructed at Teknikum.

Key publications

1. Sarlin, E., Apostol, M., Lindroos, M., Kuokkala, V.-T., Vuorinen, J., Vippola, M. & Lepistö, T. (2014), Impact properties of novel corrosion-resistant hybrid structures, Composite Structures, Vol. 108, pp. 886–893.
2. Sarlin, E., Lindroos, M., Apostol, M., Kuokkala, V-T., Vuorinen, J., Lepistö, T. & Vippola, M. (2014), The effect of test parameters on the impact resistance of a stainless steel/rubber/composite hybrid structure, Composite Structures, Vol. 113 pp. 469–475.
3. Kivikytö-Reponen, P., Laukkanen, A., Apostol, M., Waudby, R., Andersson, T., Helle, A., Valtonen, K. & Kuokkala, V-T. (2014), Modelling and testing of elastomer impact deformation under high strain rates, Tribology, Vol. 8 No. 1, pp. 48–54.
4. Vaajoki, A., Laukkanen, A., Waudby, R., Kivikytö-Reponen, P., Valtonen, K. & Kuokkala, V-T. (2014), Tribological testing and modelling of elastomeric materials, Key Engineering Materials Vol. 604, pp. 87–90.
5. Ojala, N., Valtonen, K., Kivikytö-Reponen, P., Vuorinen, P. & Kuokkala, V-T. (2014), High-speed slurry-pot erosion wear testing with large abrasive particles, submitted to Finnish Journal of Tribology.

Number of publications: 21
Number of Bachelor Theses: 1

Networks and international co-operation

- Tallinn University of Technology – communication and visits. Erosion tests showed that low impact angles are highly erosive, causing cutting of the material.
- Short-term researcher visit from the Austrian Excellence Centre for Tribology, AC2T, to test elastomers with the high-velocity particle impactor. Joint article: Ballistic and numerical simulation of impacting goods on conveyor belt rubber.

Applications & impact

- Wear modelling and a deeper understanding of polymers as wear-resistant materials can have an immediate impact in the industry through the making of better material choices in applications. Better rubber compounds can also be developed without delay through a deeper understanding of the effect of different compounding on wear resistance. Wear modelling gives systematic knowledge of material behaviour.

Wear modelling gives systematic knowledge of material behaviour

- To take modelling to the level where it could give real lifetime prediction in complex applications is itself complicated. The level achieved in the wear modelling of elastomers can nevertheless be exploited for the further development of specific wear modelling needs. It is more likely that the wear models must be tailor-made for specific applications to give true predictive information.
- **The results achieved are significant, because up to now wear modelling and understanding of polymer wear has been mostly empirical**. Wear models of polymers, especially elastomers, cannot be properly found in the literature. The information there is also often reductive: basic polymer-based information rather than concerning different rubber compounds.
- The project results consist partly of the development of empirical methods for measuring wear resistance. These results have been taken into the model to construct a tool for material wear predictions. The model and the measurement results can also be used separately.
- Commercialisation of the developed wear model lies in the future, but the benefits of deeper understanding and the different test methods have already been partly realised in the industry. Some of the results still need more practical work for full commercialisation.

PROJECT 2: New Corrosion-resistant Materials and Solutions

The aim was to develop cost-efficient stainless steels and new products to serve reliably in energy, pulp & paper industry and in other demanding applications under severe corrosive conditions.

Key outcome: New design guidelines and tools to foster the development and use of new cost-efficient material solutions. Novel alloy design principles were applied successfully to develop new ferritic stainless steel with better formability above standard grade. Close co-operation between industrial partners and research institutes during the project yielded comprehensive understanding of materials properties – from basic phenomena through to industrial applications – and created new value chains between the partners. New manufacturing methods were developed, verified and adopted for low Ni and Ni-free stainless steels. The development of laser and laser-arc hybrid welding procedures for ferritic and duplex stainless steel grades created products with the desired mechanical properties and corrosion resistance. Ferritic stainless steels proved a promising alternative to standard austenitic grades in various energy and motor applications, while duplex stainless steels demonstrated good corrosion and stress corrosion cracking resistance in modern kraft cooking processes. Electrochemical monitoring revealed itself not only an effective tool for predicting corrosion risk but also for improving process efficiency by aiding the correct timing of washing operations, opening the way to a new industrial service product.

Close co-operation between industrial partners and research institutes during the project – in addition to expediting the flow of information and creating new value chains between them – yielded comprehensive understanding of materials properties, from basic phenomena, through the influence of chemical composition and processing route on product properties, to application in industry. As one result of the project, Outokumpu is offering a new high-chromium ferritic grade, EN 1.4622 (UNS S44330), suitable for applications such as facades, elevators, catering or automotives.

Outokumpu Oy

PROJECTS:

- New-generation Ferritic Stainless Steels with Enhanced Corrosion Resistance
- Fabrication and Service Performance of Advanced Stainless Steels for Demanding Exhaust Applications
- Development of Manganese- and Nitrogen-alloyed Stainless Steels for Alkaline Environments
- New Methods for Optimising the Performance of Welds in Corrosive Industrial Environments

New Generation Ferritic Stainless Steels with Enhanced Corrosion Resistance

High-chromium nickel-free ferritic stainless steel Outokumpu 4622

Traditional austenitic stainless steels, widely known as 304(L) and 316(L), have become popular due to their easy production and generally good corrosion resistance. However, they contain relatively large amounts of nickel, an expensive alloying element subject to large price fluctuations. In the increasingly cost and environmentally conscious materials world, there is growing interest in replacing nickel with lower-cost alternatives. One such alternative is ferritic stainless steel based on chromium alloying without nickel. The problem has been that traditional ferritic stainless steels with 12–18% chromium do not perform sufficiently well in many applications: higher chromium contents are required, but these are associated with many technical problems that make them difficult to manufacture with reproducible corrosion resistance, formability and toughness. This NGF project investigated the science behind these problems and discovered ways of solving them without the need for expensive investment in new production technology. The result of extensive laboratory investigations and pilot plant production is a low-cost high-chromium ferritic stainless steel Outokumpu 4622 with 21% chromium, 0.4% copper and stabilisation elements to bind carbon and nitrogen. The steel has the characteristics listed below:

- High corrosion resistance equivalent to and sometimes superior to 304/304L austenitic grades
- Better deep drawing properties than austenitic grades
- Acceptable surface quality even after forming
- Lower and more stable price compared to austenitic grades
- Good corrosion resistance after welding
- Good machinability
- Resistant to chloride-induced stress corrosion cracking.

Figure 1. **Potential indoor solutions for Outokumpu 4622 can be easily found from e.g. catering and appliances**

PROJECT NAME

P 2 New Corrosion-resistant Materials and Solutions

NGF

CONTACT PERSON
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DAVID PORTER
UNIVERSITY OF OULU

PARTICIPANTS (ORGANISATIONS)
AALTO UNIVERSITY
OUTOKUMPU STAINLESS OY
UNIVERSITY OF OULU

PROJECT DURATION
2009 – 2014

PROJECT VALUE (EUR)
5.049 MILLION

New Generation Ferritic Stainless Steels with Enhanced Corrosion Resistance

Main targets & motivation

Stainless steels are highly alloyed steels that are used for their corrosion resistance and resistance to various chemical environments. Resistance to corrosion and chemical attack increases with increasing levels of alloying elements, most notably chromium. Traditionally, stainless steels have been made with an austenitic crystal structure, which has required the addition of nickel in use. The most commonly used stainless steels are the so-called 300 series austenitic grades that contain about 17–18% chromium and at least 7% nickel. Where the steel needs to withstand acidic environments, up to 4% molybdenum can be added to the steel, which can mean that as much as 13% nickel is needed to retain the austenitic crystal structure. Chromium is the most economical of these alloying elements to use, especially in the case of Outokumpu, which is a fully integrated steel plant with its own ferro-chromium production and adjacent chromium mine. Nickel is a relatively expensive alloying element and its price fluctuates greatly, which makes the price of austenitic stainless steels volatile, too. These factors have increased interest in the development and application of stainless steels based on iron and chromium without expensive nickel. One such way of doing this is to allow the crystal structure of the stainless steel to be ferritic. The traditional ferritic stainless steels have been based on iron alloyed with mainly just 12–18% chromium, but such steels have been inferior to the austenitic grades in respect of many corrosion properties. Consequently, the aim of the project was to explore ferritic alternatives

to austenitic grades using chromium contents greater than 18% in combination with other alloying elements, such as silicon, manganese, aluminium, copper, titanium, niobium, zirconium and vanadium, taking into account carbon and nitrogen levels, ease of production and technological properties such as corrosion resistance, formability and weldability. The main result was the developed the new high-chromium (21Cr) ferritic stainless steel grade. The grade was registered as EN 1.4622 and called later on Outokumpu 4622.

At the outset of the project, it was also known that increasing chromium content in ferritic stainless steels tends to generate low-temperature brittleness with thicknesses over 3 mm. One objective of the research was therefore to gain knowledge of how hot rolling and cooling parameters affect impact toughness. Ferritic stainless steels are also known for their susceptibility to roping, i.e. the formation of unacceptable surface striations after forming operations. It was therefore necessary to investigate how the incidence of roping in the new steel could be minimised by learning how to optimise casting with electromagnetic stirring and by understanding and controlling recrystallisation. Other goals were the optimisation of RAP process parameters, such as tandem rolling reductions, speed and annealing temperature and skin pass rolling, to give products with the best possible combination of surface quality, corrosion resistance, formability, toughness and weldability.

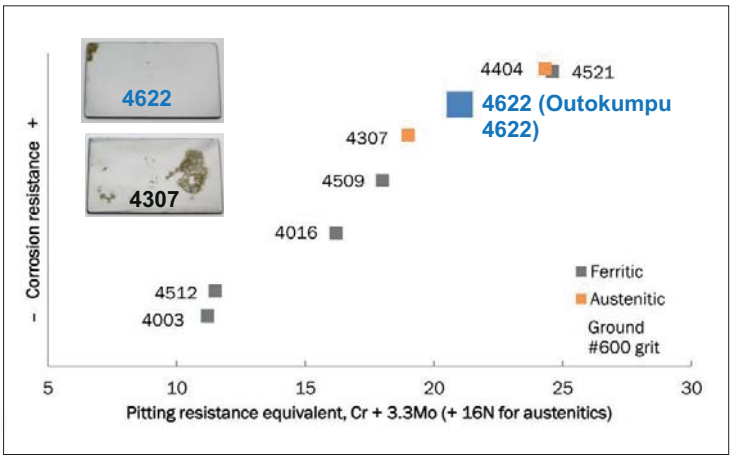

Figure 1. **The most common Outokumpu grades. The pitting resistance equivalent (PRE) calculated from formula Cr + 3.3Mo (+16N for austenitics) is one corrosion indicator. The PRE of the new Outokumpu 4622 is between typical austenitic grades 4307 (304L) and 4404 (316L). The cyclic salt spray test shows also better corrosion resistance than the austenitic grade 4307**

Production parameter – microstructure – property studies led to optimised property combinations.

Results All partners worked in close co-operation throughout the project to generate an improved scientific understanding of the behaviour of high-chromium ferritic stainless steels based on nearly 50 laboratory-scale melts. This led finally to successful full-scale industrial heats and trial deliveries. Some of the main results and deliverables are as follows:

- Alloy design principles based on the understanding gained of the effect of chemical composition, casting, hot rolling, cold rolling, annealing and pickling process parameters on mechanical and corrosion properties.
- Two flow stress models for the hot deformation of 12–27% Cr ferritic stainless steels.
- Publications on the effect of hot deformation temperature on the microstructure, dislocation structure, precipitation and texture formation during hot rolling and hot band annealing of high-Cr ferritic stainless steels, and use of this information for improving the conventional hot rolling routines in order to achieve better texture structure in the final product for improved deep drawability.
- Three reports concerning the effects of e.g. chromium and stabilising elements on corrosion resistance.
- Understanding of the effect of differences in casting and hot rolling operations between laboratory- and production-scale materials with respect to crystallographic texture and formability.
- Formability of the final product (as measured by the Lankford coefficient r) 90% better than standard ferritic stainless steels through optimisation of chemical composition, stabilisation, cold rolling reduction and annealing temperature.
- Roping was successfully minimised by applying optimised process parameters.
- Brittleness caused by the formation of chromium carbides and nitrides during high-temperature processing can be avoided by microalloying with the stabilising elements.
- Understanding the effect of cooling rate on e.g. hot band 475 °C embrittlement.
- Feedback from potential customers regarding trial deliveries of the new Outokumpu 4622 ferritic stainless steel.
- Understanding the influence of stabilising elements and their ratio on weldability. By using Nb-rich stabilisation instead of Ti-rich, the reduction in impact toughness in the heat-affected zone can be minimised.

- Understanding the influence of welding on corrosion resistance of the Outokumpu 4622. Nb-rich stabilisation is superior compared to others. Postweld treatments are always mandatory for adequate corrosion performance, as iron-rich weld oxides are detrimental to corrosion resistance.
- In Nb-rich ferritic stainless steels the columnar grained welds may have reduced properties. A novel approach was used to promote grain refinement in autogenous GTA welds.
- The weldability of the new Outokumpu 4622material is similar to that of 1.4509. The preferred use is a minimum amount of stabilising elements for full stabilisation, and low heat input for optimum toughness properties. Excessive use of stabilising elements reduces toughness of the base metal and heat-affected zone considerably, but may provide improvements regarding corrosion resistance e.g. in dissimilar welds.

Deep drawability almost double that of standard austenic stainless steels

Key publications

1. Mehtonen, S., Karjalainen, P. & Porter, D. (2014), Modelling of the high-temperature flow behaviour of stabilised 12–27 wt.% Cr ferritic stainless steels. Materials Science & Engineering A, Vol. 607, pp. 44–52.
2. Mehtonen, S., Karjalainen, P. & Porter, D. (2013), Hot deformation behaviour and microstructure evolution of a stabilised high-Cr ferritic stainless steel. Materials Science & Engineering A, Vol. 571, pp. 1–12.
3. Mehtonen, S., Palmiere, E., Misra, D., Karjalainen, P. & Porter, D. (2014), Dynamic restoration mechanisms in a Ti-Nb stabilised ferritic stainless steel during hot deformation. Materials Science & Engineering A, Vol. 601, pp. 7–19.
4. Mehtonen, S., Palmiere, E., Misra, D., Karjalainen, P. & Porter, D. (2014), Microstructural and texture development during multi-pass hot deformation of a stabilised high-Cr ferritic stainless steel. Accepted for publication in ISIJ International, currently in press.
5. Anttila, S. & Porter, D.A. (2014), Influence of shielding gases on grain refinement in welds of stabilised 21% Cr ferritic stainless steel. Accepted for publication in Welding in the World, currently in press.

Number of publications: 13
Number of Doctoral Theses: 1
Number of Licentiate Theses: 1
Number of Master's Theses: 1
Number of patent applications/patents: 1

Networks and international co-operation

Saara Mehtonen's three-month visit in the Department of Materials Science and Engineering at the University of Sheffield and co-operation with Prof. Eric Palmiere on the plane strain hot deformation of high-chromium ferritic stainless steels improved understanding of hot deformation processes, i.e. restoration mechanisms and texture development (publications 3 and 4 above). Transmission electron microscopy of high-chromium steel after simulated hot deformation was achieved in co-operation with Prof. R. Devesh K. Misra at the Center for Structural & Functional Materials of the University of Louisiana at Lafayette, USA. This co-operation improved understanding of the details of the restoration mechanisms operating in these high-chromium ferritic stainless steels. Several potential customers from around the world have accepted trial deliveries of the new steel and provided feedback regarding its performance on their production lines and in their products.

Applications & impact

After substantial laboratory-scale studies on numerous trial compositions, this radically new stainless steel has reached the trial production stage and is currently being tested and evaluated by several potential users across the globe. Laboratory testing has already demonstrated that the steel outperforms equivalent steels and has corrosion resistance at least on a par with the austenitic grades it is intended to replace. The steel has potential for wide application in general use, for example in the automotive industry, and for building facades, elevators, household items, kitchen utensils, panels and storage tanks.

Radically new low-cost high-chromium ferritic stainless steel (Outokumpu 4622) developed to trial production and delivery stage

During the course of this NGF project, the science behind these problems has been investigated, and ways discovered of solving the problems. The result of extensive laboratory investigations and pilot plant production through close co-operation between the industrial and university partners is a low-cost high-chromium ferritic stainless steel Outokumpu 4622 with 21% chromium, 0.4% copper and appropriate stabilizing additions.

PROJECT NAME
P 2 New Corrosion-resistant Materials and Solutions

FABRICS

Fabrication and Service Performance of Advanced Stainless Steels for Demanding Exhaust Applications

Strong fluctuation in raw material prices has forced companies around the world in the metals and engineering industry to seek economically stable materials. Ferritic stainless steels (FeCr-base alloys with no or low Ni content), are considered an alternative for demanding applications such as energy conversion and exhaust systems, where resistance to corrosion, excellent thermal properties, good mechanical strength and competitive price are appreciated. This project obtained deep understanding and knowledge on fabricability, product properties and performance in high-temperature engine applications.

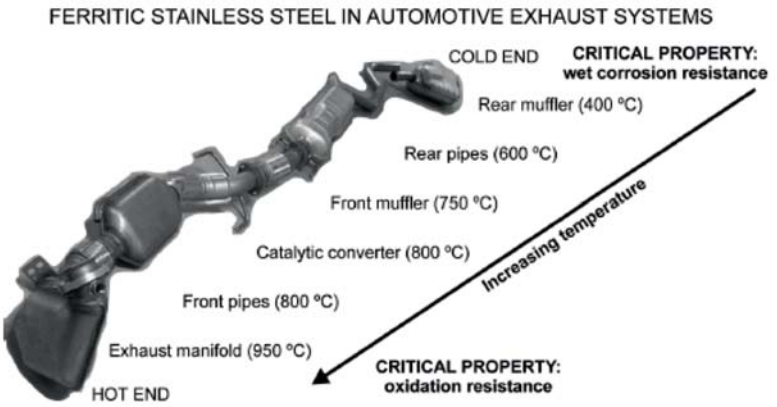

Figure 1. **The diverse constraints for ferritic stainless steel materials in an automotive exhaust system (The photo by courtesy of Outokumpu Stainless Oy)**

Fabricability and product properties proven

Simulations made by the University of Oulu's Centre for Advanced Steels Research showed that significant changes in microstructure occur during constant and cyclic high-temperature service, which decreases yield strength and hardness at room temperature if the service temperature is extremely high, at around 800 °C. According to further simulations, the cooling rate during the production process was found to have a significant effect on the yielding behaviour and formability of the steel. Comprehensive information on how alloying affects the high-temperature properties and formability of the steel was attained and can be used to improve the production process and the properties of the steel. Studies of microstructure and formability interactions revealed that texture, segregation and precipitation phenomena have a strong effect on mechanical properties and formability. Long heat treatment reduces high-temperature strength and lowers strain-hardening capability as shown in the work carried out by the Department of Materials Science at Tampere University of Technology. The texture of the final product can be affected at the early stage of the manufacturing process by modifying process practices in the steel-melting shop. Outokumpu Stainless Oy is exploiting this knowledge in process development.

Straightforward strain-rate sensitivity of ferritic stainless steels simplifies design

Straightforward strain-rate sensitivity of ferritic stainless steels simplifies design. It was shown with advanced modified tensile Hopkinson Split Bar tests (Tampere University of Technology, Department of Materials Science) that the strain-rate-sensitive behaviour of ferritic stainless steels can be modelled in a relatively straightforward way, notably simplifying the analysis and design of load-bearing structures, for example in the automotive industry and transport vehicle business, compared to the corresponding austenitic grades.

Successful tube-welding trials were conducted using stabilised ferritic grades as a raw material. Tube weld properties, especially microstructure and corrosion resistance, were studied.

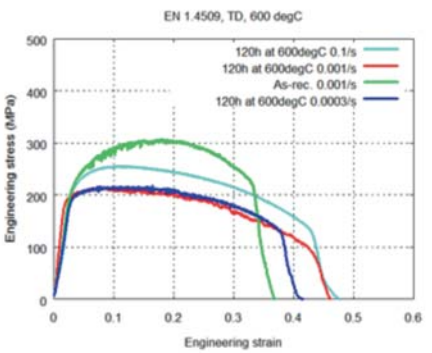

Figure 2.
Long heat treatment reduces high-temperature strength and lowers strain-hardening capability

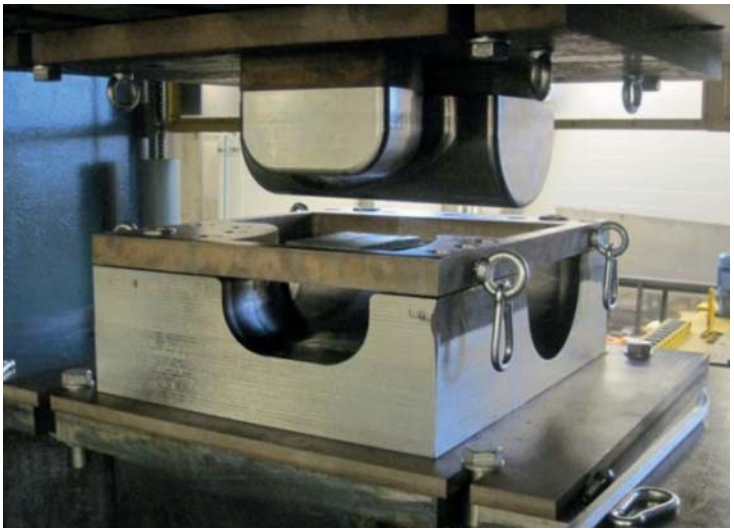

Figure 3. **Deep drawing of exhaust branch (by courtesy of Antti-Jussi Ristola)**

Figure 4. **Laser welding of ferritic stainless steel tubes (by courtesy of OSTP Finland Oy)**

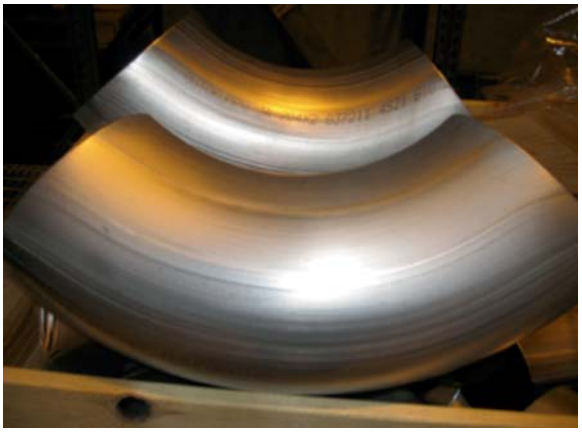

Figure 5. **Laser weld ferritic stainless steel tubular products (by courtesy of OSTP Finland Oy)**

High-temperature performance and ageing

In his PhD work, Harri Ali-Löytty (Tampere University of Technology, Optoelectronics Research Centre) showed that at elevated temperatures, oxidation resistance can be enhanced by controlled surface treatments or by microalloying with elements that affect the oxide layer formation through segregation and interfacial oxidation. It was found that by careful optimisation of the Nb microalloying, the formation of the insulating SiO_2 at the oxide–metal interface can be controlled. Upon ageing, formation of Si-containing Laves (FeNbSi)-type

intermetallic compounds in the bulk resulted in non-uniform distribution of Si oxide at the interface. Besides exhaust systems and components developed in this project by Wärtsilä Finland Oy and Dinex Ecocat Oy, the insights into the influence of niobium microalloying on the electrical properties of ferritic stainless steels also benefit other high-temperature application areas, of which the solid-oxide fuel cells are a prospective example.

Applications in exhaust systems, catalysators, solid-oxide fuel cells

VTT Technical Research Centre of Finland developed procedures and validated new materials for aggressive high-temperature energy applications. Overall, the future engine environments are very challenging for materials, **but new ferritic stainless steel grades were proven to have good high-temperature oxidation and corrosion resistance** and in many cases are promising alternatives to austenitics grades. For example, ferritic stainless steel grades performed better compared to the austenitics with similar Cr content at 700 °C in environments simulating the operating conditions of a selective catalytic reduction (SCR) system which was applied to reduce diesel engine emissions. For very aggressive conditions, more alloyed materials are needed. At high temperature with some moisture in the gas mixture, the protective chromia layer starts to evaporate and some other alloying elements, e.g. Al, are needed to improve the formation of protective oxides. In this context, the behaviour in exhaust system middle-and cold-end conditions were also evaluated. Work done in the Department of Materials Science at Tampere University of Technology showed that the level of **chromium alloying determines the overall corrosion performance under simulated exhaust gas condensate conditions**. The higher the chromium level, the better the corrosion performance and, by implication, the lower the chromium level, the poorer the corrosion performance. Stabilisation through both niobium and titanium alloying is recommended for alloys intended for automotive exhaust systems that reach the temperature of 600 °C, to avoid intergranular corrosion. Wärtsilä Finland Oy exploited this knowledge when selecting materials for the new double-wall exhaust pipe, designed to enable a lighter exhaust pipe insulation box and to meet the corrosion challenges caused by the SCR environment. Dinex Ecocat Oy benefited from this when evaluating new ferritic stainless grades for catalysator casings to meet the future demands.

Microstructure, segregation, precipitation & high-temperature oxidation phenomena in ferritic grades understood

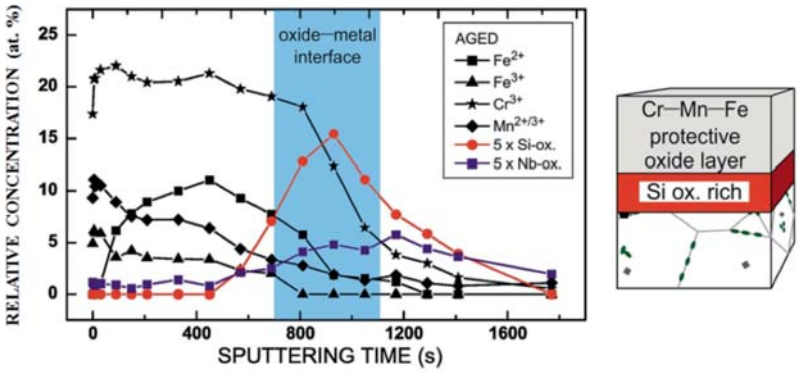

Figure 6. **Si oxide shown to enrich at the interface – XPS analysis of high-temperature segregation and oxidation in aged (120 h at 800 °C) EN 1.4509 after 30 min oxidation in air at 650 °C–**

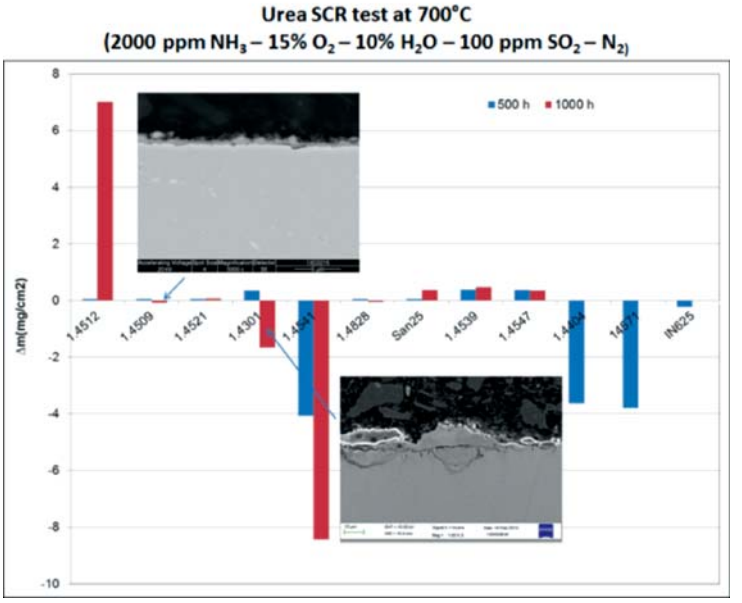

Figure 7. **New ferritic stainless steel grades 1.4509 and 1.4521 are stable and a promising alternative to austenitics in SCR applications**

Figure 8.
New double-wall exhaust pipe in engine test (courtesy of Wärtsilä Finland Oy)

PROJECT NAME

P 2 New Corrosion-resistant Materials and Solutions

FABRICS

CONTACT PERSON

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OUTOKUMPU STAINLESS OY

PEKKA POHJANNE
VTT TECHNICAL RESEARCH CENTRE OF FINLAND

PARTICIPANTS (ORGANISATIONS)

OUTOKUMPU STAINLESS OY, WÄRTSILÄ FINLAND OY, DINEX ECOCAT OY, OSTP FINLAND OY, IITTALA GROUP OY AB, TAMPERE UNIVERSITY OF TECHNOLOGY (DEPARTMENT OF MATERIALS SCIENCE AND OPTOELECTRONICS RESEARCH CENTRE), UNIVERSITY OF OULU (CENTRE FOR ADVANCED STEELS RESEARCH, CASR), VTT TECHNICAL RESEARCH CENTRE OF FINLAND

PROJECT DURATION

2009 – 2014

PROJECT VALUE (EUR)

4.447 MILLION

Cost-effective solutions for clean energy

Fabrication and Service Performance of Advanced Stainless Steels for Demanding Exhaust Applications

Main targets & motivation

The driving force and motivation for the project was the necessity of cleaner energy and the tightening of environmental regulations. Although Finnish know-how in motor and catalytic converter technology was originally at a good level, it was recognised that new and cost-effective solutions are required to keep the competitive edge.

The main aim of the project was to develop alternatives to traditional austenitic stainless steels. The search for solutions focused on advanced ferritic stainless steels, which are known to offer a cost-efficient and sustainable solution in several fields, with proper surface, corrosion and mechanical properties for a variety of applications. Their use was hindered by a lack of knowledge concerning their fabrication properties, possible limitations and performance in extreme high-temperature operating conditions.

To generate this knowledge, the following research targets were set out:

- To gain understanding of production technologies to obtain desired material properties
- To gain understanding of fabricability issues to foster development of new products

- To acquire knowledge on oxidation, corrosion and fatigue at high temperatures for evaluation of new stainless steel grades and products for demanding applications
- To provide material selection and fabrication guidelines for advanced ferritic stainless steels.

Results

- Advanced production technologies were used to produce stabilised ferritic stainless steel grades with improved formability
- Welding procedures were developed to produce products with the desired mechanical properties and corrosion resistance from ferritic stainless steel grades
- New simulation tools were developed, verified and adopted for formability and deep drawing to foster product development
- Ferritic stainless steel grades were proven to have good mechanical properties combined with high-temperature oxidation and corrosion resistance, and are in many cases a promising alternative to austenitics grades.

New ferritic steels, fabrication, welding, simulation tools – performance proven in real applications

Key publications

1. Isakov, M. (2012), Strain Rate History Effects in a Metastable Austenitic Stainless Steel. Doctoral Theses, Tampere University of Technology.
2. Ali-Löytty, H. (2013), Microalloying Mediated Segregation and Interfacial Oxidation of FeCr Alloys for Solid-Oxide Fuel Cell Applications. Doctoral Theses, Tampere University of Technology.
3. Juuti, T., Rovatti, L., Mäkelä, A., Karjalainen, L.P. & Porter, D. (2014), Contribution of Mo and Si to Laves-phase Precipitation in Type 444 Steel and Its Effect on Properties, Journal of Alloys and Compounds, in reviewing process.
4. Tuurna, S., Pohjanne, P., Filander, S. & Silvonen, A., Materials performance with Na2CO3-V2O5-CaSO4 deposit under moist synthetic air. NACE. International Corrosion Conference Series, Vol. 5, pp. 3993–4001.
5. Huttunen-Saarivirta, E., Kuokkala, V-T. & Pohjanne, P. (2014), Thermally grown oxide films and corrosion performance of ferritic stainless steels in simulated exhaust gas condensate. Corrosion Science, Vol. 87 (2014),pp. 344–365.

Number of publications: 22
Number of Doctoral Theses: 2
Number of Master's Theses: 2
Number of patent applications/patents: 1

Networks and international co-operation

Research co-operation was realised with the Ohio State University, Columbus, OH, USA. PhD student Matti Isakov from the Department of Materials Science at Tampere University of Technology was working at the Department of Mechanical and Aerospace Engineering for six months during 1.11.2010–30.4.2011 for his thesis. Continuous research visits, throughout the project, to MAX IV Laboratory (Lund, Sweden) by Tampere University of Technology – Optoelectronics Research Centre, provided advanced synchrotron radiation-based methods for analysis of surface phenomena throughout the project. Research time at such large-scale international research infrastructure is granted based on peer-reviewed applications and based on scientific excellence.

Applications & impact

Effective value chain for research and business

- Wärtsilä Finland Oy invented and patented a new stainless steel pipe structure and exhaust system with enhanced properties.
- OSTP Finland Oy got new experience on how to form, laser weld and produce ferritic stainless steel tubular products. New products complying to supply standards are in test production for applications like exhaust systems, carbon capture and storage (CCS), fluidized boilers and gas cleaning.
- Dinex Ecocat Oy evaluated new ferritic stainless grades for catalysator casings to meet the future demands. New ferritic stainless steel grades are promising alternative to austenitics in SCR applications
- Iittala (Fiskars Home, Sorsakoski Cookware Factory) gained knowledge from formability and deep drawing issues. This is now exploited also in consumer sector to manufacture cookware and cutlery.
- Outokumpu Stainless Oy gained new information and experience on the final product properties of stabilized ferritic stainless steels in general and how the modifications in process practices effect on these properties.
- Close cooperation between industrial partners and research institutes during the project yielded comprehensive understanding of materials properties from the basic phenomena to the industrial applications and expedited the flow of information between the partners.
- The project provided an excellent platform for researcher training for both academy and Finnish metal industry.

Development of Manganese and Nitrogen Alloyed Stainless Steels for Alkaline Environments

The pulping process (separating cellulose and hemicellulose from wood chips) involves use of high-temperature alkaline and sulphidic environments which are highly corrosive towards the structural materials. The main target of the present project is to prevent catastrophic failure of process equipment caused by stress corrosion cracking (SCC) of high-strength austenitic and duplex stainless steels in alkaline sulphidic environments by developing understanding of their SCC mechanisms.

The research problems this project set out to solve are a) to develop a mechanistic model for evaluation of new stainless steel grades for demanding applications in energy and pulp and paper industries, b) to gain knowledge to allow the production of new stainless steel grades with optimal alloying compositions (replacing Ni with Mn- and N-alloying) and pretreatments, c) to provide the ability to prolong the service life of stainless steel structures by selecting initially more appropriate steel grades and manufacturing methods or by applying electrochemical protection and d) to contribute to structural safety and design methods in order to avoid catastrophic failures related to SCC and hydrogen embrittlement.

Monitoring & controlling electrochemical potential is key for safe operation of a pulp mill

Field measurements in the evaporator unit of the pulp mill provided the participants with a monitoring tool for detecting process conditions that make structural materials susceptible to SCC. A corrosion potential lower than $E < -50$ mV was shown to be detrimental. It was noted that correct timing of equipment-washing operation was vital. Laboratory studies revealed that ferritic stainless steels are highly susceptible to SCC in high-temperature alkaline sulphidic environments, and thus not suitable structural materials in hot black liquor (HBL) conditions. Duplex stainless steels showed in general only very limited

SCC susceptibility in an HBL environment. A trend was established whereby increasing the nickel concentration in duplex stainless steels helped to avoid SCC. SCC in austenitic stainless steel AISI 304 in the same environment could be prevented by polarisation (anodic protection). This opens a possibility for a new industrial service product.

Understanding material performance in specific corrosion environments, effects of alloying, pretreatments & electrochemical potential

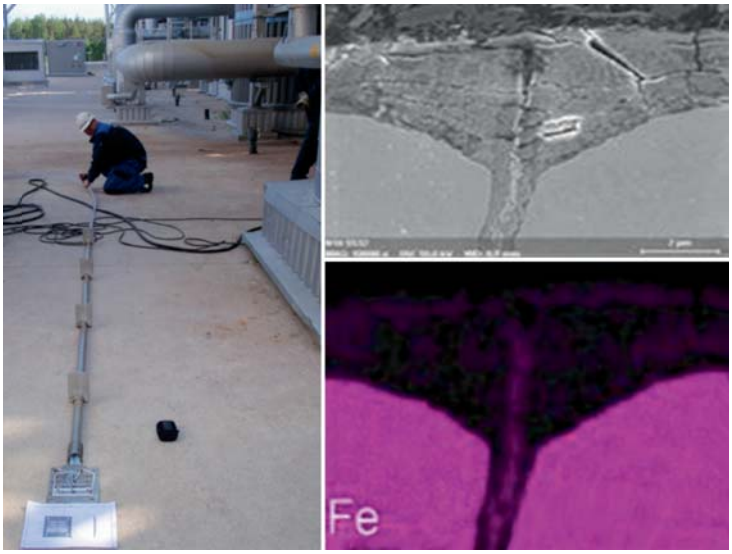

Figure 2. **Field corrosion measurements at a pulp mill conducted by Savcor Forest Ltd (left). Scanning electron microscope picture of a stress corrosion crack in AISI304 austenitic stainless steel after two-week exposure to a simulated hot black liquor environment (right), showing a flux of iron emanating from the middle of the crack (selective dissolution of iron)**

PROJECT NAME

P 2 New Corrosion-resistant Materials and Solutions

MN-STEELS

CONTACT PERSON

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PROJECT DURATION

2009 – 2014

PROJECT VALUE (EUR)

1.253 MILLION

Development of Manganese and Nitrogen Alloyed Stainless Steels for Alkaline Environments

Main targets & motivation

The pulping process (separating cellulose and hemicellulose from wood chips) involves use of high-temperature alkaline and sulphidic environments which are highly corrosive towards the structural materials. The main target of the present project is to prevent stress corrosion cracking (SCC) of high-strength austenitic and duplex stainless steels in alkaline sulphidic environments by developing an understanding of their SCC mechanisms.

Increased lifetime & safety by taking control of stress corrosion cracking phenomena

The research problems this project set out to solve are:

a) to develop a mechanistic model for evaluation of new stainless steel grades for demanding applications in energy and pulp and paper industries

b) to gain knowledge to allow the production of new stainless steel grades with optimal alloying compositions (replacing Ni with Mn- and N-alloying) and pretreatments

c) to provide the ability to prolong the service life of stainless steel structures by selecting initially more appropriate steel grades and manufacturing methods or by applying electrochemical protection

d) to contribute to structural safety and design methods in order to avoid catastrophic failures related to SCC and hydrogen embrittlement.

Results

- Duplex (austenitic-ferritic) stainless steels are suitable for structural use in high-temperature alkaline sulphidic environments – increasing [Ni]>4% helps in avoiding SCC
- SCC of austenitic stainless steel AISI304 in high-temperature alkaline sulphidic environments can be prevented by anodic protection
- Ferritic stainless steels are not suitable structural materials in high-temperature alkaline sulphidic environments as they are highly susceptible to SCC
- According to laboratory studies and field exposures, Mo alloying has an adverse effect and Cr alloying a positive effect on the general corrosion resistance of stainless steels, especially in Na_2S-containing caustic environments.

Promising laboratory test results verified by extensive field tests

Key publications

1. Pohjanne, P., Vepsäläinen, M., Saario, T., Sipilä, K., Romu, J., Saukkonen, T., Hänninen, H., Heikkilä, M., Berg, C-G, Pulliainen, M. & Ohligschläger, T. (2014), Effect of Electrochemical Potential on Stress Corrosion Cracking Susceptibility of EN 1.4301 (AISI 304) Austenitic Stainless Steel in Simulated Hot Black Liquor. To be submitted for publication in Corrosion NACE – journal.
2. Pohjanne, P., Vepsäläinen, M., Saario, T., Sipilä, K., Romu, J., Saukkonen, T., Hänninen, H., Heikkilä, M., Berg, C-G, Pulliainen, M. & Ohligschläger, T. (2014), Effect of nickel content on corrosion resistance of duplex stainless steels in simulated hot black liquor. To be submitted for publication in Corrosion NACE – journal.
3. Vepsäläinen, M. , Pohjanne, P., Heikkilä, M., Berg, C.-G., Romu, J., Saukkonen, T., Hänninen, H., Ohligschläger, T. & Pulliainen, M. (2013), Effect of alloy composition and temperature on corrosion behavior of stainless steels in hot alkaline solutions. Corrosion 2013, 17–21 March 2013, Orlando, FL, United States: NACE International. NACE - International Corrosion Conference Series.
4. Leinonen, H., Pohjanne, P., Chasse, K., Singh, P., Romu, J., Saukkonen, T. & Hänninen, H. (2012), Effect of alloy composition on stress corrosion cracking susceptibility of duplex stainless steels in hot alkaline sulfide solution. Corrosion 2012, Salt Lake City, UT, 11–15 March 2012. NACE. International Corrosion Conference Series, Vol. 7, pp. 5780–5800.

5. Leinonen, H., Pohjanne, P., Romu, J., Saukkonen, T., Schildt, T. & Hänninen, H. (2012), Selective dissolution and stress corrosion cracking susceptibility of austenitic and duplex stainless steels in sodium sulfide containing alkaline solutions. Corrosion 2012, Salt Lake City, UT, 11–15 March 2012. NACE. International Corrosion Conference Series, Vol. 2, pp. 1364–1375.

Number of publications: 7
Number of Doctoral Theses: 1

Networks and international co-operation

A co-operation was launched with Georgia Institute of Technology, School of Materials Science and Engineering, Atlanta, USA, together with Aalto University. Visiting scientist periods were realised within this co-operation, and Mr Kevin Chasse finalised his PhD thesis. FPInnovations-Paprican, Vancouver, BC, Canada

Applications & impact

The new finding that **austenitic stainless steel EN 1.4301 can be protected against SCC in hot black liquor (HBL) by anodic protection** opens a possibility for a new industrial service product. This is directly in the business area of Savcor Forest Ltd – among the company's main products are anodic and cathodic protection systems.

Ferritic stainless steels are highly susceptible to SCC in high-temperature alkaline sulphidic environments and are thus not suitable structural materials in HBL conditions. This, and the result that **duplex stainless steels need to have more than 4% nickel in order to avoid stress corrosion cracking in an HBL environment**, directs Outokumpu Ltd in their customer technology support on material selection issues and Andritz Ltd in their choice of structural materials in pulping industry equipment.

New Methods for Optimising the Performance of Welds in Corrosive Industrial Environments

Fluctuation of the nickel raw material price in the global market has resulted in demand for low-Ni alloyed stainless steels, i.e. duplex, Mn-alloyed austenitic and ferric grades. The use of low-Ni grades is expected to grow in both pulp & paper and process industries. However, in order to substitute existing construction materials, there is a need for a comprehensive understanding of both joining and joint performance in the service environment. Comparable experimental data on corrosion properties, as well as instructions and codes of practice for welding manufacture for demanding structures, are not yet available.

Laser-arc hybrid welding can be simply described as a fusion-welding process where both a laser beam and welding arc – typically MIG/MAG or TIG – are focused simultaneously in the same weld pool. This hybrid technology has a number of advantages, but in this context the most important is the use of external filler material to modify the metallurgical composition of the resulting weld. The objectives of the project's laser-arc hybrid welding experiments were to produce welded test samples for both mechanical and corrosion characterisation, and to develop process know-how for successful joining of these novel materials.

Laser-arc hybrid welding trials were conducted on three base materials, two ferritic (1.4509 and 1.4622) and one duplex (1.4162) stainless grades, using four different types of filler metals and three joint configurations. The aim of the trials was to evaluate if weld metallurgy – microstructure, grain morphology, austenite/ferrite balance, etc. – can be controlled by modifying filler metal composition and/or dilution behaviour by using different groove geometries.

It was discovered that dilution rates can be controlled by using a tailored joint geometry. The dilution rates achieved varied between ~ 35–65% with the same filler metal, depending on the joint configuration used. The characterisation results showed that with the welding consumables used, weld microstructural features such as grain morphology, mode of weld solidification, austenite/ferrite balance, etc.,

can also be modified by altering the weld chemistry through filler metal selection. Further adjustments can be made by combining these two, i.e. by using a tailored combination of joint configuration and filler metal selection.

Finer weld solidification structure was achieved with the two ferritic grade base materials 1.4509 and 1.4622 by using a filler material – joint type combination that enables the change of solidification mode from Ferritic (F) to Ferritic-Austenitic (FA). With the lean duplex base material 1.4162 it was discovered that although the solidification mode can be shifted from F to FA by changing the filler metal, austenite content in welds dominates over ferrite for all joint configuration/dilution rates used when type superaustenitic 904L filler metal is applied. From the point of view of research, and especially characterisation method, electron backscatter diffraction (EBSD) proved to be an excellent tool in phase balance determination of the weld cross-sections with respect to accuracy and resolution, ease of use and characterisation time.

Quick and efficient phase distribution analysis with EBSD

Finally, it can be concluded that these welding experiments provide new data and know-how on laser-arc hybrid welding of novel ferritic and duplex stainless steel grades. The results gave guidelines to and understanding of interdependencies between the welding process conditions and weld geometry, filler metal selection with respect to dilution behaviour, and effect of weld chemistry on weld solidification and resulting microstructures. The results can be used, for example, by steel manufacturers in their steel development and customer service, by OEMs in their product and production development, and by end-users in their maintenance and service activities.

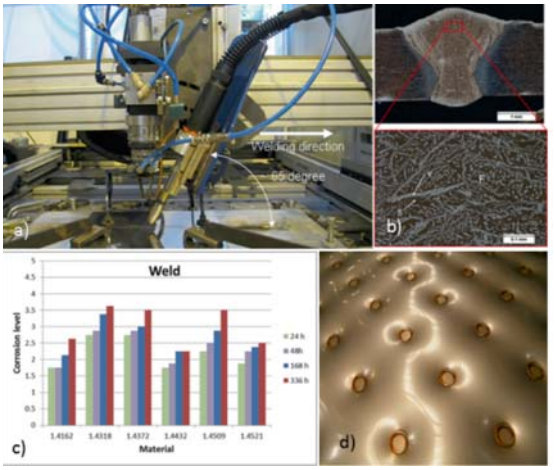

Figure 1. **a) Laser-arc hybrid welding arrangement allowing, b) microstructural tailoring for e.g., c) optimised corrosion resistance of d) components in true service conditions**

PROJECT NAME

P 2 New Corrosion-resistant Materials and Solutions

X-WELD

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AALTO UNIVERSITY

PROJECT DURATION

2010 – 2014

PROJECT VALUE (EUR)

1.155 MILLION

New Methods for Optimising the Performance of Welds in Corrosive Industrial Environments

Main targets & motivation

- Nickel raw material price volatility has resulted in demand for low-Ni alloyed stainless steels
- The use of these grades is expected to grow in both pulp & paper and process industries
- Substitution of existing construction materials requires comprehensive understanding of both joining and joint performance in the service environment
- Comparable experimental data on corrosion properties, as well as instructions and codes of practice for welding manufacture for demanding structures are not yet available
- Knowledge on the localised corrosion and repassivation behaviour of new stainless grades in chloride-sulphate solutions
- Determination of the mechanical characteristics and structural behaviour of novel stainless steels under static and dynamic loading conditions
- Understanding of the interaction between weld metallurgy and corrosion resistance of welded joints in novel stainless steel grades in relevant service environments
- Preparing welding and manufacturing procedure specifications to ensure competitive products, with special emphasis put on advanced, high-productivity welding technologies.

Enhanced manufacturing characteristics and tailored service properties through laser hybrid welding

Results

- Laser-arc hybrid welding trials were conducted on three base materials, two ferritic and one duplex grade stainless steel, using four different types of filler metals and three joint configurations
- The weld metallurgy – microstructure, grain morphology, austenite/ferrite balance, etc. – can be controlled by modifying filler metal composition and/or dilution behaviour by using different groove geometries
- Dilution rates can be controlled by using a tailored joint geometry, dilution rates varying between ~ 35–65% with the same filler metal, depending on the joint configuration used
- With the welding consumables used, weld microstructural features such as grain morphology, mode of weld solidification, austenite/ferrite balance, etc., can also be modified by altering the weld chemistry through filler metal selection
- Further adjustments can be made by combining these two, i.e. by using a tailored combination of joint configuration and filler metal selection
- From the point of view of characterisation method, electron backscatter diffraction (EBSD) proved to be an excellent tool in phase balance determination of the weld cross-sections with respect to accuracy and resolution, ease of use and characterisation time.

Key publications

1. Sirén, M., Pohjanne, P., Kujanpää, V., Hirn, J., Romu, J. & Heikkinen, H-P. (2014), Mechanical and corrosion properties of welded joints in new generation ferritic and duplex stainless steels. Materials Science Forum 783–786, pp. 1003–1008. doi:10.4028/www.scientific.net/MSF.783-786.1003.
2. Anttila, S., Lauhikari, V. & Heikkinen, H-P. (2013), Ferriittisten ruostumattomien terästen hitsien jälkikäsittelyt. Hitsaustekniikka 63, pp. 10–18.
3. Sirén, M. (2012), New generation ferritic and duplex stainless steels: Preliminary study on mechanical and in-service properties of welded joints. Nordic Welding Conference 2012 (NWC2012), Oslo, 4–5 October 2012, Norsk Sveiseteknisk Forbund.

4. Nevasmaa, P., Sirén, M., Karjalainen-Roikonen, P., Hirn, J., Romu, J., Hänninen, H., Sieppi, V., Heikkinen, H-P., Manninen, T. & Säynäjäkangas, J. (2012), New generation ferritic and duplex stainless steels. Preliminary study on mechanical and in-service properties of base materials and welded joints. 65th Annual Assembly of the International Institute of Welding, Denver (CO), USA, 8–11 July 2012, IIW-Doc. IX-2394-12 (IX-H-770-12). International Institute of Welding.

Number of publications: 6

Applications & impact

The results will be used by

- Steel manufacturers (e.g. Outokumpu Stainless) in their steel development and customer service
- End-users (e.g. Andritz) in their product and production planning and maintenance service
- Research institutes (e.g. VTT and Aalto) in their research services and educational purpose.

PROJECT 3: Extreme Service Conditions

The project was aimed at developing effective new solutions for applications in extreme service and operational conditions, such as combinations of highly corrosive environment, erosion, severe thermal and mechanical fatigue, and high service temperature. Good co-operation between the project partners brought the development and validation in plant tests of innovative coatings for boiler applications with operation at extreme high temperature. New computational tools were also developed for design and risk assessment in extreme service conditions. The project enabled greatly improved understanding of the degradation mechanisms of related phenomena, which will have a huge influence on future studies.

The trend today is fuel flexibility. Multiple fuel types are co-burned, posing new challenges for boiler operators. Here, chlorine-induced corrosion lies at the heart of limitations on the desired flexibility. The MATEXON project tackled this issue with innovative coatings, with promising results. A further result was the creation of a network between experts for future studies.

Fortum Oyj

PROJECTS:

- Materials for Extreme Conditions of Sustainable Processes
- Materials Performance under Severe Cyclic Loading

Materials for Extreme Conditions of Sustainable Processes

The MATEXON project developed a **new material solution to protect fireside surfaces against high temperature (500—700 °C) chlorine corrosion in severe combustion environments of the energy and process industry**. The proposed solution is based on introducing an innovative coating as a surface layer to prevent chlorine and oxygen diffusion into the substrate to be protected.

Tailored coatings protect against chlorine attack in severe conditions of the energy and process industry

The solution is to produce spray coatings with nickel-rich lamellar splat boundaries in the coating, as shown in Figure 1. This new solution, the Cl-trap coating, has been developed and patented by VTT. In the Cl-trap coating the base powder 50Ni50Cr is coated with a material that prevents chlorine penetration to the base metal surface through the lamellar boundaries. This coating can be performed by either milling or chemical plating. The coated powder is thermally sprayed (e.g. HVOF) on to the substrate material, forming a highly corrosion-resistant coating, with extra chlorine blockage on the lamellar boundaries. Coatings made following this method were produced and tested in a highly corrosive chlorine environment, as well as at site with a corrosion probe in real boiler conditions.

Combining nanomaterials, thermal spraying and application know-how

Promising results were obtained with the new Cl-trap materials. Layered Ni barriers between 50ni50Cr coatings retard high-temperature chlorine corrosion by preventing chlorine from penetrating through lamellar boundaries to the substrate material. With this solution, the lifetime of boiler tubes in highly aggressive chlorine environments can be increased significantly. In the future the material solution obtained can be adapted to different environments.

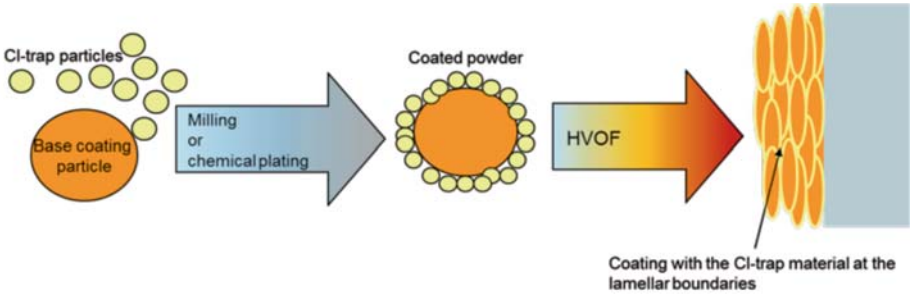

Figure 1. **Principles of a Cl-trap coating**

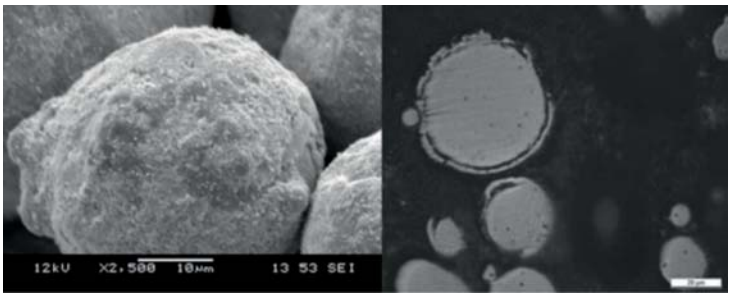

Figure 2. **Produced chlorine trap powder (50Ni50Cr + nano Ni coating) before thermal spraying**

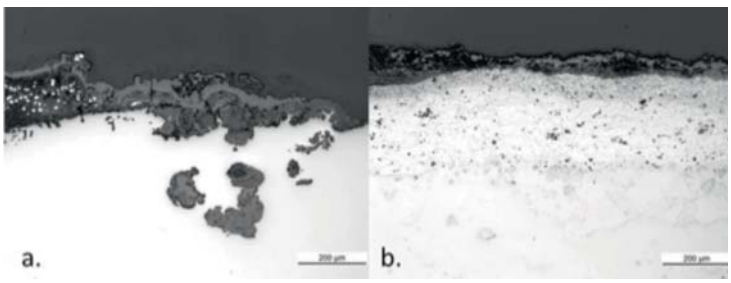

Figure 3. **Coating after the Kauttua on-site validation a) the reference 50Ni50Cr and b) the Cl-trap 50Ni50Cr coating**

Another alternative route studied was so-called **overlay welds**, manufactured using three different filler metal additives. Kanthal A-1 welding wire was explored as alumina-forming overlay coating and as a silica former, where filler metal with a composition of Fe-12Cr-2Si was chosen. The purpose of the forming alumina/silica layer is to prevent the diffusion of oxygen, chlorine and other environmental impurity ions through the oxide scale into the metal and thus effectively prevent and retard the further high-temperature corrosion reaction. In addition to these, another alumina-forming prototype overlay weld was manufactured using dual wires during the welding process and

by manually controlling the forming composition. The goal was an Al content of around 10 wt.% but this was not achieved, resulting in inadequate corrosion resistance for the manually composed coating.

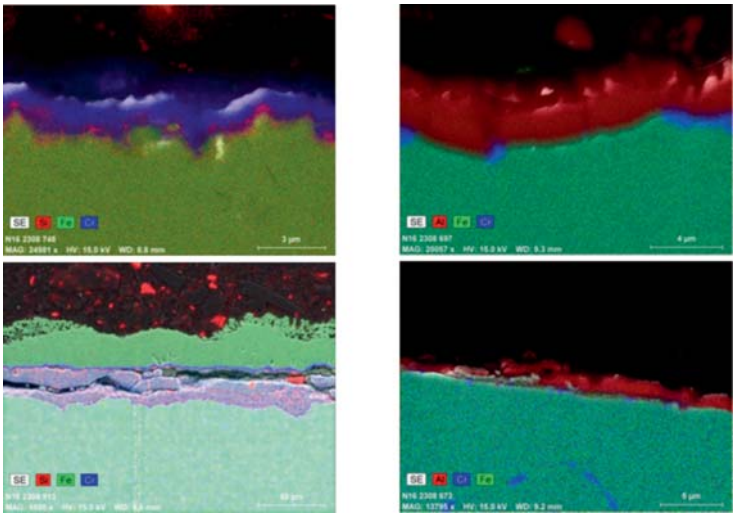

Figure 4. **Corrosion products formed on Kanthal A-1 after testing (KCl at 600 °C)**

The corrosion resistance of the overlay welds was tested in aggressive KCl environments (600 °C) and in probe tests in actual boiler environments. Study was also made of the resistance of the coatings against high-temperature oxidation (950 °C).

The main results of the overlay weld corrosion resistance studies are:

- Kanthal A-1 formed an external alumina scale during exposure to high temperature, while Fe-12Cr-2Si formed an external chromia scale with a network of silica containing oxide particles underneath, preventing the diffusion of oxygen ions inwards and chromium ions outwards at the metal–scale interface.
- The oxidation resistance of both Kanthal A-1 and Fe-12Cr-2Si coatings was found to be very good due to the oxide scales they formed on their surface.
- Preoxidised Kanthal A-1 coating performed better in KCl tests than Kanthal A-1 and Fe-12Cr-2Si coatings in as-welded state. An external alumina scale therefore turned out to be more beneficial from the corrosion-resistance point of view than a silica scale, at least in a KCl-containing environment (presumably Cl-containing in general).

- In the first probe test executed, both coatings lost their passivity to the environment, allowing the chlorine to penetrate through the oxide scale, causing the material to lose its corrosion resistance.

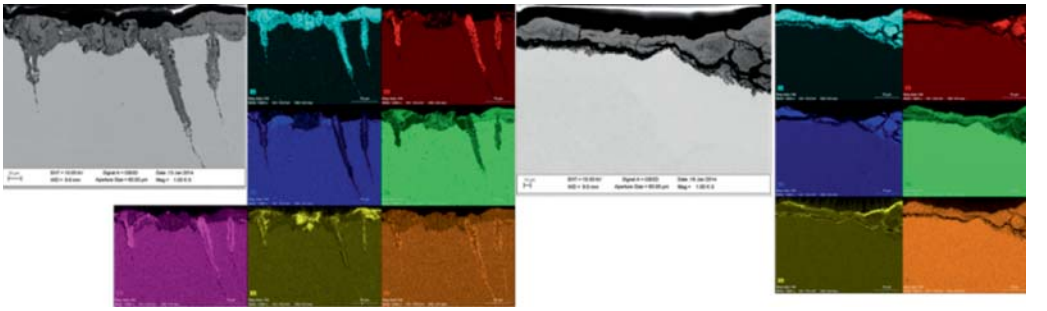

Figure 5. **Corrosion products formed on Fe-12Cr-2Si after testing (KCl at 600 °C)**

PROJECT NAME

P 3 Extreme Service Conditions

MATEXON

CONTACT PERSON

OSSI HIETANEN
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PROJECT DURATION

2010 – 2014

PROJECT VALUE (EUR)

0.816 MILLION

Materials for Extreme Conditions of Sustainable Processes

Main targets & motivation

The MATEXON project's main objective was the development of radically new innovative materials and protective solutions for surfaces under highly demanding service conditions at temperatures of 500–700 °C. The foreseen applications included critical high-temperature surfaces in the energy and process industry, for example in advanced combustion and severe environments of highly corrosive fuels. A project research topic that was advancing well was the new concept for preventing the corrosion of boiler materials at high temperatures in environments with high chlorine content, by preventing chlorine and oxygen diffusion into the metal through use of an innovative coating.

Results

The project had a unique combination of researches and industrial partners throughout the whole process values chain. The project developed a new material solution to protect fireside surfaces against high-temperature (500–700 °C) chlorine corrosion in severe combustion environments of the energy and process industry. The solution is based on introducing an innovative coating as a surface layer to prevent chlorine and oxygen diffusion into the substrate to be protected. Though further validation of the new material is still needed, the results obtained from this project are highly promising.

New material solution to protect fireside surfaces against high-temperature (500–700 °C) chlorine corrosion

The industrial partners defined the need for the new material solution, and provided environment data for the first stages of the solution. At the first stage, the problem was tackled by a thorough state-of-the-art review and thermodynamic calculations. On the basis of the design, the research parties suggested a novel solution

for the problem at hand; production of tailored coatings to prevent the diffusion of chlorine to the substrate material. The solutions included alumina-forming overlay welds and special chlorine trap thermal sprayed coatings, and enhanced powder metallurgical materials to demonstrate an ideal dense coating.

Innovative coatings provide significantly longer lifetime for bioenergy boilers

The targeted tailored coatings were produced and optimised by an industrial partner and the research parties. The performance of the coatings was first tested in laboratory using accelerated high-temperature corrosion tests in a chlorine environment, and high-temperature erosion tests. These test indicated that the solution would have the desired performance. Some of the results have been published at international conferences.
Based on the laboratory investigations, the coatings with the most potential were subjected to on-site validation testing with on-line probes. The validation was performed in close collaboration with all project partners. The plant tests were made at the Kauttua power plant and MF Joutseno pulp mill. The validation testing at Joutseno is still ongoing, but the Kauttua experiments have already provided extremely promising results.

The result of the project was a solution for tackling chlorine-induced high-temperature corrosion. Though the validation tests are still in progress, the results are extremely promising. With some additional optimisation of the coating process the solutions will expand the lifetime of boiler tubes at the most critical locations.

Key publications

1. Sarikka, T. (2013), Properties of ferritic Fe-Cr-Al, alumina-forming austenitic and Fe-Cr-Si alloy coatings at elevated temperatures, Master's Thesis Aalto University School of Engineering, Department of Engineering Design and Production.
2. Sarikka, T., Ilola, R., Hänninen, H., Pohja, R. & Tuurna, S. (2012), Manufacturing of Fe-Cr-Al weld overlay coatings for high-temperature applications, 4th International Conference on the Integrity of High Temperature Welds and 9th International Conference on Creep and Fatigue at Elevated Temperatures, UK, Minerals and Mining.
3. Sarikka, T., Ilola, R., Hänninen, H. & Pohja, R. (2013), Corrosion resistance of Kanthal A-1 and Fe-12Cr-2Si alloy coatings in a Cl-containing environment, Baltica IX, International Conference on Life Management and Maintenance for Power Plants, Pertti Auerkari & Juha Veivo (eds.),VTT Technology series 106, pp. 500–512.
4. Yli-Olli, S., Suhonen, T., Virta, J., Holmström, S., Varis, T., Tuurna, S. & Kinnunen, T. (2013), A material solution against

fireside chloride corrosion, Baltica IX, International Conference on Life Management and Maintenance for Power Plants, Pertti Auerkari & Juha Veivo (eds.),VTT Technology series 106, pp. 513–524.

5. Tuurna, S., Pohjanne, P., Yli-Olli, S., Heikkilä, J. & Meskanen, J. (2014), Boiler material optimisation with corrosion probe measurements, Article in review for the 10th Liège Conference on Materials for Advanced Power Engineering in September 2014.

Number of publications: 4
Number of Master's Theses: 1

Networks and international co-operation

In the project international cooperation was performed with MIT, USA and European materials suppliers. Also some of the tests were performed in collaboration with the Technical University of Tallinn.

Applications & impact

The project has produced promising results with new thermal sprayed coatings and overlay welds. With the new solutions, the lifetime of boiler materials in highly aggressive chlorine or severe erosion environments can be increased significantly. The results obtained produced added value for all industrial partners involved. The material solutions achieved can be adapted to different future service conditions.

Materials Performance under Severe Cyclic Loading

Environmental effect (Fen) in piping fatigue analysis

This project **developed a totally new analysis method for piping fatigue**. In this analysis, stress and fatigue calculations are performed at different points of the pipe cross-section, and stresses due to pressure, forces, moments, and temperature distribution are calculated at the calculation points along time. Stress intensification factors are applied to obtain stress and strain components and the stress intensities. The environmental effect (Fen factor) is then calculated by integrating strain quantities along time. Development of this new method allows the Fen calculation and fatigue analyses to be made automatically without extra conservatism.

RI-ISI analysis allows focus of NPP piping system inspections at locations with the highest risks

The VTT contribution to the project was the development of a quantitative risk-informed in-service inspection (RI-ISI) analysis procedure for Nuclear Power Plant (NPP) piping systems, and development of a computer code for analysing the propagation of the flow-accelerated corrosion (FAC).

Propagation of flow-accelerated corrosion can be assessed with the developed FAC code

This RI-ISI analysis procedure allows quantitative assessment of the physical risks associated with the NPP piping components and systems. Unlike existing qualitative RI-ISI analysis procedures, this procedure takes account of the geometry, material properties, loads and relevant degradation mechanisms concerning the NPP piping components. This is a clear improvement. The piping component failure probabilities are computed by applying probabilistic fracture mechanics (PFM). The risks are computed quantitatively using the PFM analysis results and suitable consequence measures. Based on the results obtained with the new procedure, the inspection locations and intervals can be optimised in terms of risk. This will also ensure that the total risk associated with the earlier deterministic inspection programme is not exceeded. When shifting from a deterministically

based to a risk-informed inspection programme, the number of locations to be inspected can be reduced considerably. Figure 1 shows an example for three inspection strategies concerning time-dependent leak probabilities for an NPP pipe weld of austenitic stainless steel (diameter 325 mm and wall thickness 17.5 mm) where the degradation mechanism considered is stress corrosion cracking (SCC) and the initial flaw examined is an internal circumferentially oriented semi-elliptic surface crack.

NPP piping components of a certain material type can be prone to FAC under certain flow conditions. This degradation mechanism causes local wall thinning, and if not detected in inspections can lead to a leak. A computer code was prepared to enable better assessment of the susceptibility to and effect of FAC. The physical effects of FAC are then computed with the KWU-KR model. This model allows the computation of the propagation of FAC both deterministically and probabilistically.

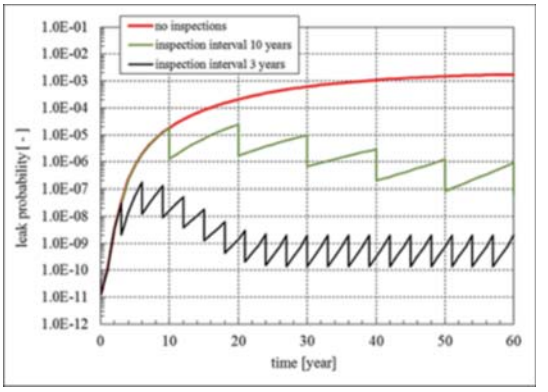


Figure 1. **PFM analysis result example showing leak probabilities for an NPP pipe weld when the assumed time of operation is 60 years**

The quantitative RI-ISI analysis procedure developed for NPP piping systems allows optimisation of the inspection programmes, thus leading to a reduction in risks, inspection work, radiation exposure and inspection costs. The FAC computer programme also improves assessment of the inspection targets/locations.

Safety, reliability and cost-efficiency for nuclear plant piping system inspection

Weld residual stress relaxation was studied experimentally using pipe welds manufactured by TVO, with the original materials and weld process specifications used during construction of the OL1/OL2 plants. Exposure to the expected thermal and mechanical loads during service was simulated for the welds prior to the residual stress

measurements. The results showed that mechanical and thermal loading changes the distribution and magnitude of weld residual stresses. An important observation was that the weld residual stresses are relaxed and changed from tensile to compressive during thermal loading. This is beneficial in preventing initiation and propagation of stress corrosion cracks. The **combination of finite element modelling, experimental thermal fatigue simulation and residual stress measuring of NPP welds, performed in the project, is unique worldwide**. The results can be used in predicting residual stresses and SCC during plant operation, and are beneficial in planning inspections and repairs.

The fatigue threshold regime is usually the governing part in the fatigue analysis of forest machine components, which are typically machined, welded or cast steel structures. Linear-elastic fracture mechanics (LEFM) and elastic-plastic fracture mechanics (EPFM) models were developed using a multi-linear isotropic hardening model to calculate the threshold limit and crack closure of fatigue cracks. It was shown that the theoretical size of the plastic zone near the crack tip at the threshold regime was close to the grain size of the studied materials, 20MnCrMo5 and GJS-500-7.

AISI H13 tool steel produced using different manufacturing routes was studied as an alternative material in applications demanding extreme wear resistance. Typically, tool steels are used in applications where loading is mainly compressive. The results showed no clear difference in fatigue properties between the different manufacturing routes (conventional vs. ESR).

The influence of cold-work on the elastic properties of austenitic stainless steels was studied using the ultrasonic pulse-echo method and tensile tests with partial unloading cycles. The results show that the apparent Young's modulus of austenitic stainless steel decreases rapidly with increasing pre-strain, gradually approaching an asymptotic value. New test methods for characterising the mechanical behaviour of stainless steel sheet metals were developed and implemented in the Outokumpu Tornio Research Centre. The results are used in predicting the behaviour of formed stainless steels products under mechanical loading.

PROJECT NAME

P 3 Extreme Service Conditions

MACY

CONTACT PERSON

PAUL SMEEKES, TEOLLISUUDEN VOIMA OY

RISTO ILOLA AALTO UNIVERSITY

PARTICIPANTS (ORGANISATIONS)

FEMDATA OY, FORTUM NUCLEAR SERVICES OY, JOHN DEERE FORESTRY OY, METSO MINERALS OY, OUTOKUMPU STAINLESS OY, WÄRTSILÄ OYJ ABP, VTT TECHNICAL RESEARCH CENTRE OF FINLAND

PROJECT DURATION

2009 – 2014

PROJECT VALUE (EUR)

3.816 MILLION

Materials Performance under Severe Cyclic Loading

Main targets & motivation

- The project targets were to develop and begin use of state-of-the-art fatigue design methods and rules for demanding applications that meet special requirements, such as high reliability (quantified survival probability), severe loading conditions (LCF and/or very HCF), varying and/or elevated temperature, and environment.
- The original project length was three years. Since, with the exception of TVO and FEMdata, the other industrial partners did not continue for the fourth and fifth year of the DEMAPP programme, the targets were focused on development of nuclear power plant (NPP) fatigue analysis, risk-informed in-service inspection (RI-ISI) and flow-accelerated corrosion (FAC). In addition, Aalto University's target was to evaluate the effect of thermal load cycles and pressure test on residual stresses of NPP piping.

Results

- Development of a new fatigue analysis for NPP piping which can be used under the TVO PAMS.
- Development of a quantitative risk-informed in-service inspection (RI-ISI) analysis procedure for NPP piping systems.
- Development of a computer code for analysing the propagation of flow-accelerated corrosion (FAC).
- Verifying that weld residual stresses are relaxed during thermal cycling in NPP piping.
- Development of fatigue threshold regime estimations.

Thermal cycling relaxes weld residual stresses

Key publications

1. Cronvall, O. (2013), Quantitative Risk Informed In-Service Inspection (RI-ISI) procedure for TVO Summary. Research Report VTT-R-06628-13, Technical Research Centre of Finland (VTT), Espoo, Finland.
2. Kaunisto, K. (2013), Implementation of Probabilistic Flow-Accelerated Corrosion Procedure. Research Report VTT-R-05104-13, Technical Research Centre of Finland (VTT), Espoo, Finland.
3. Aalto, M. (2014), Residual stress relaxation due to cyclic thermal loads in BWR nuclear power plant pipe welds Licentiate of Science Thesis. Aalto University. To be published.
4. Chauhan, M., Solin, J., Alhainen, J., Manninen, T., & Lönnqvist, C. (2012), Cyclic Behaviour and Fatigue of Stainless Steels. La Metallurgia Italiana, 9, 13–18.
5. Manninen, T., Solin, J., Alhainen, J. & Chauhan, M. (2011), Influence of Cold-Work on the Elastic Properties of Austenitic Stainless Steels. In: Nicodemi W., Nilsson, J-O. & Tiziani, A. (Eds.), Proceedings of the 7th European Stainless Steel Conference. Como, Italy, 21–23 September. Associazione Italiana di Metallurgia.

Number of publication : 18
Number of Licentiate Theses: 1
Number of Master's Theses: 2

Networks and international co-operation

The MACY project was run in close and active co-operation with the industrial and research partners. Production of experimental data and its validation in computational models was made possible within this consortium by the DEMAPP programme.

Applications & impact

The results of the MACY project allow expanded and more accurate capabilities for assessing the structural integrity and operational safety of NPP piping components and systems.

PROJECT 4: Friction and Energy

The aim was to develop techniques for energy reduction in industry and society through new low-friction and tailored tribological solutions.

Key outcome: New design guidelines based on friction modelling were laid down for more accurate prediction of fretting damage in medium-speed diesel engines. This reduces time to market for new products and lessens the risk of catastrophic failure. Incorporating carbon nanoparticles in the contact surface layers of wind turbine gear transmissions reduced transmission friction and wear by 50% and improved torque density by 30%. Optimised surface topography lowered friction by 35% in surfaces designed for water removal elements in paper machines, while implementing advanced composite coatings on hoisting wheels in wire contact for elevators and cranes improved the friction by 35% and reduced wear by 80%.

Testing and modelling of the sheave wear and rope contact made us more confident about the birth of phenomena we have been encountering in the field for decades. The creation of an engineering tool, together with the connection between tests at material and system level, also helped to inspire use. We shall take advantage of this newly acquired knowledge in our future products. Some promising new ideas have emerged which will allow us to make further leaps in materials.

Kone Oy

Development of new hard coatings gave us direct opportunities in new product offerings. Deeper knowledge of the mechanisms of successful performance regarding cover materials and cover structures encourages us to develop our products further.

Valmet Technologies Oyj

PROJECTS:

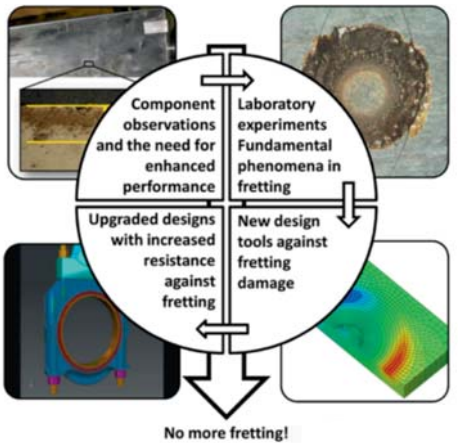
- Fretting Damage in Mechanical Engineering
- Low Friction in Lubricated Contacts
- Low Friction in Process Environment
- High-friction Low-wear Contacts
- Low Friction in Hydraulics
- Friction Energy and Economic Impact

PROJECT NAME
P4 Friction and Energy

FREDA

Fretting Damage in Mechanical Engineering

Fretting fatigue and fretting wear are difficult to tackle and high risks for highly loaded assemblies



More accurate prediction of fretting damage and lifetime of components increases cost-efficiency and reliability

Fretting fatigue and fretting wear are regarded as the plagues of modern industry. The main objectives of the project are to model and evaluate the friction, fretting fatigue and fretting wear in contacting surfaces and to seek preventive solutions for fretting damage. Modelling results need to be verified by experiments, and the fundamental knowledge of fretting mechanism improved. The ultimate goal is to improve design and shorten development time in engine and machine assemblies transferring high traction loads and operating under high-cycle fatigue conditions. The main research topics involved are fretting behaviour in complete contacts, evolution of the friction coefficient in fretting contact, materials and surface treatments such as fretting damage inhibitors and the advanced machine assembly-level simulation of fretting damage.

More realistic modelling of friction

The evaluation of contact stresses requires accurate predictions for the friction coefficient, which is not known in all situations. Fretting tests with sphere-on-plane contact geometry have shown non-Coulomb friction behaviour. Partial slip fretting conditions were simulated using the 3D finite element method, including a developed variable friction coefficient model. Additionally, non-Coulomb friction was measured and characterized in detail in gross sliding fretting conditions. Friction studies concerning the non-Coulomb gross slip and partial slip friction coefficient provide insight into the frictional behaviour of the fretting contact. Theory and tools can be used in practice when simulating the real contact problems, and they provide more accurate fretting damage prediction than traditional contact simulation methods. They can also be used in component-level design optimisation against fretting damage.

Longer fretting fatigue life with surface treatment

The effect of nitriding and shot peening on the fretting and plain fatigue behaviour of a high-strength quenched and tempered steel and a nodular cast iron was studied in complete contacts, i.e. contacts having "sharp" contact edges. In the case of steel, nitriding increased the fretting fatigue limit by 150% and the plain fatigue limit by around 25%. Shot peening increased the fretting fatigue limit by 110% and the plain fatigue limit by around 10%. With cast iron, shot peening increased both the fretting and plain fatigue limits by about 20%. The residual compressive stresses created by a surface treatment can therefore be very helpful in terms of preventing fretting failure or increasing fatigue lives. Results can be used directly at the design stage and, especially in the case of contacts where high stress concentrations exist near the surface, improvements gained in terms of safety against fretting.

Effect of contact edge geometry

Contact edge geometries were analysed experimentally and by means of FE simulations. The initial pure "sharp"-ended fretting contact edge was slightly rounded. It was found that the fretting fatigue lives remained at very similar levels, i.e. the rounding had no major effect on fatigue life, as shown in the figure below. Modelling results agree with the experimental results shown in the figure. The FE model showed that high contact stresses continued to prevail even though the contact edge was slightly rounded. Results can be used when choosing the contact geometries. Engineers generally consider rounded shapes to be safer.

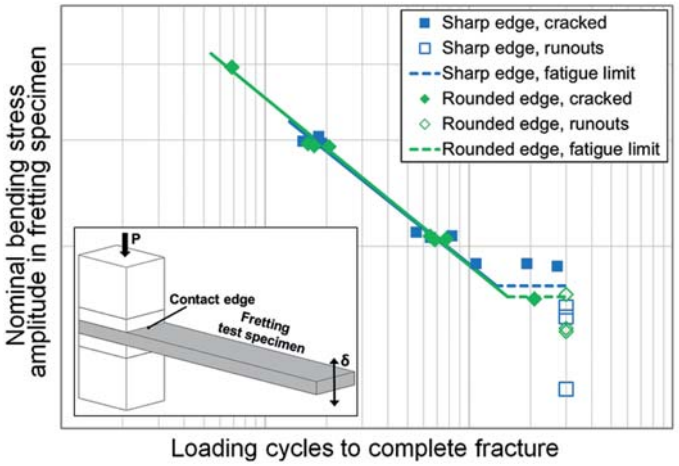


Figure 1. **Experimental S-N fretting fatigue test curves for sharp and rounded contact edge cases**

Fretting analysis of medium-speed diesel engine

In component-level simulations, friction coefficient plays an especially important role as it dominates slip and shear traction behaviour and clearly depends on local contact response, which also makes it non-uniformly distributed. In order to consider this in simulations, a user subroutine for frictional contact in Abaqus software was made. The routine allows the user to define non-Coulomb and non-uniform friction coefficient evolution during the analysis, and also facilitates extracting custom contact results. The routine was tested during a case study of a connecting rod, and the results presented at ISFF7 in Oxford, while the manuscript was submitted for the Tribology International Special Issue. More theoretical development is nevertheless needed to simulate the friction coefficient more realistically in general contact conditions.

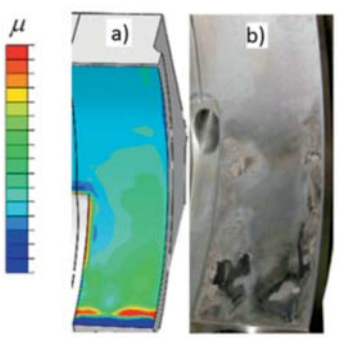


Figure 2. **a) Simulated friction coefficient distribution in a real engine component b) Fretting damage after test in a running engine**

PROJECT NAME
P4 Friction and Energy

FREDA

CONTACT PERSON	PARTICIPANTS (ORGANISATIONS)	PROJECT DURATION	PROJECT VALUE (EUR)
ANTTI MÄNTYLÄ WÄRTSILÄ FINLAND OY **ARTO LEHTOVAARA** TAMPERE UNIVERSITY OF TECHNOLOGY	**WÄRTSILÄ FINLAND OY** **METSO PAPER OY** **TAMPERE UNIVERSITY OF TECHNOLOGY**	**2010 – 2013**	**0.739 MILLION**

Fretting Damage in Mechanical Engineering

Main targets & motivation

Fretting – very small movement between surfaces – carries the risk of unexpected, catastrophic failures

- Fretting may occur between any two contacting surfaces where short-amplitude reciprocating sliding occurs over a large number of cycles. This oscillatory movement can take place at the micrometer level, even without gross sliding of the contacting surfaces. This causes fretting wear of the surfaces and fretting fatigue, which can lead to a rapid decrease in fatigue life. In gross sliding conditions the whole contact is sliding, but in partial slip conditions part of the contact is still sticking.
- Motivation: Fretting fatigue and fretting wear is considered to be the plague of modern industry. Often it has disastrous consequences as fatigue cracks are allowed to initiate and grow unobserved within a contact.
- The main objectives are to model and evaluate friction, fretting fatigue and fretting wear in contacting surfaces and to seek preventive solutions for fretting damage. The ultimate goal is to improve design and shorten development time in engine and machine assemblies that transfer high traction loads and operate under high-cycle fatigue conditions.
- The novelty and added value this work provides is the advanced approach for dealing with friction in contact surfaces by focusing on the variable coefficient of friction (COF) concept. Important progress is made in the experimental and numerical analysis of fretting fatigue behaviour in complete contacts, i.e. contacts having “sharp” contact edges. In addition, novel experimental data is produced employing various material

combinations and surface treatments in fretting conditions. From a technological point of view, numerical tools have been improved for both cases: variable COF concept and complete contacts. These tools can be used in component-level simulations to optimise designs against fretting damage.

Novel concept, experimental data and numerical tools together

- The research problem focuses on the modelling and evaluation of friction, fretting fatigue and the fretting wear mechanism with different types of contacts under partial, mixed and gross slip conditions.

Results

- Fretting combined with sharp-edge contact (high concentrated contact stresses) greatly decreases the fatigue life of high-strength steel compared to plain fatigue life, but has only minor effects with nodular cast iron.
- Nitriding and shot peening of the high-strength steel significantly increases the fretting fatigue life of sharp-edged complete contacts.
- Slight rounding of an initially sharp contact edge does not increase fretting fatigue life.
- Under complete contact, fretting fatigue life decreased when there was an increase in contact pressure.
- Fretting fatigue performance of high-strength steel was impaired when it was fretted with an aluminium bronze counter surface under high load.
- A variable friction model was developed, based on fretting scar asperity interactions. This explains the experimentally obtained non-Coulomb frictional behaviour in gross sliding fretting conditions.
- Another variable friction model was developed that explains the non-Coulomb frictional behaviour of fretting point contact where COF is dependent on the displacement amplitude in partial slip conditions.
- A modelling methodology based on fretting was developed and applied successfully in diesel engines.
- The Ruiz parameter has been applied successfully in the design optimisation process of diesel engine components.
- When the experimental results and developed methods are applied to real components, a good correlation is obtained between the simulations and tests in a running engine.

Key publications

1. Mäntylä, A., Könnö, J., Hintikka, J. & Lehtovaara, A.(2013), Fretting Analysis Methodology for the Connecting Rod of Medium-Speed Diesel Engine, Submitted for the Tribology International Special Issue.
2. Hintikka, J., Lehtovaara, A., & Mäntylä, A. (2013), Fretting fatigue and friction of quenched and tempered steel in dry contact with aluminium bronze, Wear 308, pp. 155-165, doi: 10.1016/j.wear.2013.07.002.
3. Juoksukangas, J., Lehtovaara, A. & Mäntylä, A. (2013), The effect of contact edge geometry on fretting fatigue behaviour in complete contacts, Wear 308, pp. 206-212, doi: 10.1016/j.wear.2013.06.013.
4. Juoksukangas, J., Lehtovaara, A. & Mäntylä, A. (2012), Development of a complete contact fretting test device, Proc. IMechE, Part J: J. Engineering Tribology, 227(6),pp. 570–578, doi: 10.1177/1350650112466162.
5. Lehtovaara, A. & Lönnqvist, C. (2011), Modelling and analysis of fretting wear in rough point contacts in partial slip conditions, Proc. IMechE, Part J: J. Engineering Tribology, 225(10), pp. 986–998, doi: 10.1177/1350650111417215.

Number of publications: 25
Number of Doctoral Theses: 2 in progress
Number of Master's Theses: 1
Number of patent applications/patents: 1

Networks and international co-operation

International collaboration was realised with fretting experts from Oxford University (UK).

Applications & impact

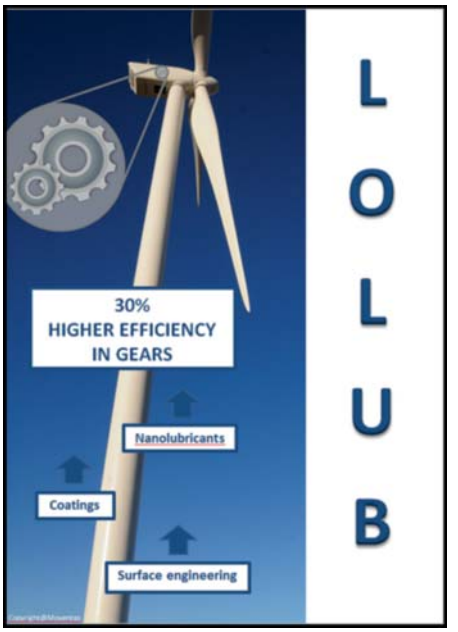
- The results will be used in the design of bolted connections, press fits and shrink fits of high-performance medium-speed diesel engines and paper machine roll heads. Joints can be optimised against fretting damage using the methods developed and the test data obtained.
- Commercialisation of results: A connecting rod and counterweight for a crankshaft have already been successfully optimised and an increased safety margin for fretting damage obtained. New designs are used in current and future engines.

The results make it possible to predict fretting damage in real components more accurately by using modern simulation methods. This reduces the need for expensive and time-consuming component-level testing and the risk of catastrophic failure. Some of the results can be used immediately at the design stage without the need for simulation.

PROJECT NAME
P4 Friction and Energy

LOLUB

Low Friction in Lubricated Contacts



1. RESULT I: CARBON COATINGS – LABORATORY TESTS

Up to 20% reduction in friction was achieved with the combination of improved surface finish and carbon-based coatings (hydrogen free diamond-like carbon and W-doped carbon). The results were demonstrated in laboratory tests in lubricated rolling contacts to simulate real components.

2. RESULTS II: CARBON COATING – FIELD TESTS

A significant decrease of friction and increase in load capacity was found for carbon coated gears in the gear tests. Coated gears can achieve 30% higher contact pressure on the gear tooth flank.

Friction losses of the gear tooth contact were decreased by 16%. Tests with the coated gears also showed a beneficial effect as a run-in surface.

With polished gears, contact pressure on the gear tooth flank can be increased by 18%, and gear contact friction decreased by 17%. An important finding was that the polishing process does not need to achieve a mirror-like surface, with hardly any texture on the surface, in order to achieve the best results in gear tooth surface durability and efficiency.

Figure 1. **Test gear**

3. RESULT III: 50% LOWER FRICTION USING CARBON NANOMATERIALS

Carbon nanomaterials (diamond nanoparticles and graphene oxide/silica composites) enabled a decrease of 50% in friction and wear in liquid-lubricated high-load steel-steel contacts. These novel materials provide tomorrow's lubrication today. Carbon nanomaterials provide tailored solutions for nearly all lubricated high-load contact conditions.

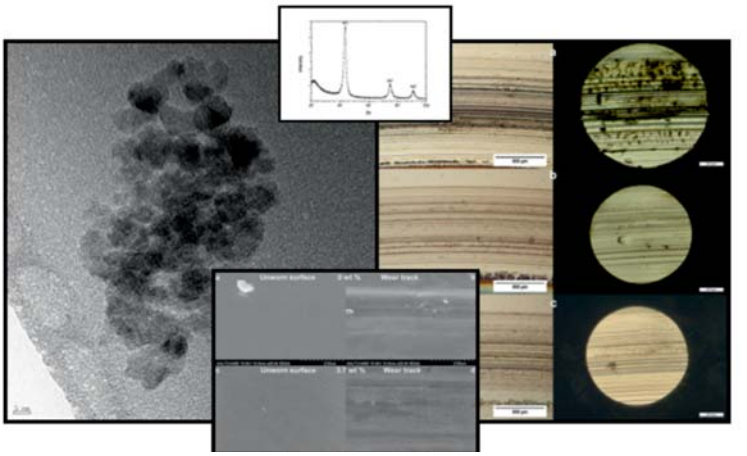


Figure 2. **Friction and wear testing using carbon nanolubricants**

PROJECT NAME

P4 Friction and Energy

LOLUB

CONTACT PERSON	PARTICIPANTS (ORGANISATIONS)	PROJECT DURATION	PROJECT VALUE (EUR)
JUKKA ELFSTRÖM MOVENTAS GEARS OY **JARI KOSKINEN** AALTO UNIVERSITY	**MOVENTAS GEARS OY** **AALTO UNIVERSITY** **VTT TECHNICAL RESEARCH CENTRE OF FINLAND** **UNIVERSITY OF JYVÄSKYLÄ**	**2010 – 2014**	**1.577 MILLION**

Best gears for wind

Low Friction in Lubricated Contacts

Main targets & motivation

The main motivation was to develop novel surface engineering methods for producing components such as gears for significantly higher loading conditions. The aim was to lower the coefficient of friction (dynamic and static) and improve the durability of components by applying the strategy of thin films, surface polishing and development of novel carbon-based lubricant additives. In more detail, the different strategies were:

Surface engineering methods for producing components for high loading conditions

- Surface engineering by polishing and thin film deposition
  Development of a coating process with significantly better load-carrying capability suitable for high power density lubricated contact
- CNP
  Understanding and testing of the basic tribological behaviour of carbon nanoparticles (CNP) in high mechanical load in lubricated conditions. Developing and testing novel lubricant additives.
- Static friction
  Understanding and development of static friction testing
- Super finishing
  Development of new super finishing processes by using nanoparticles, self-conditioning coatings and ion beam sputtering.

Results

1. Surface roughness had the major effect on friction performance in rolling contact: based on twin disc tests, reducing the surface roughness reduced friction by 11–18%. Further improvement could be achieved by using the carbon-based coatings. The optimized surface finish, surface roughness and coating provided friction reduction and improved gear performance. This enabled energy savings and lighter designs for more economical, sustainable and reliable gears.
2. Nanoparticles (CNP) improved the friction and wear performance of liquid-lubricated, high-load steel contacts in water and ethylene glycol lubrication in Pin-On-Disc tests. CNP additives decreased friction and wear coefficients by up to 50%. One of the main mechanisms was observed to be incorporation of nanoparticles into the tribolayer. These additives can be used in novel lubricant solutions, such as water lubrication, and further developed for oil lubrication.
3. A measurement device and two methods for static friction measurements were developed and systematic static friction results reported for the first time. High static friction was measured, both in dry and lubricated conditions, for a typical bearing combination of steel and tin alloys. Low static friction was observed for materials applying carbon coatings.
4. Low energy directional ion beam sputtering was successfully demonstrated for polishing of several metal surfaces. The treatment reduced roughness below the levels obtainable by conventional polishing techniques. High-energy implantation of boron and nitrogen ions improved surface hardness and durability.

Carbon nanomaterials: 50% decrease in friction and wear performance

Key publications

1. Ronkainen et al. (2014), The effects of surface finishing in oil-lubricated, carbon-coated high-load steel-steel contacts, Tribology International, to be submitted.
2. Elomaa et al.(2013), Diamond nanoparticles in ethylene glycol lubrication on steel-steel high load contact, Diamond & Related Materials 34, pp. 89–94.
3. Elomaa et al. (2014), A comparison of tribological properties of evenly distributed and agglomerated diamond nanoparticles in lubricated high-load steel-steel contact, Tribology International 71, pp. 62–68.
4. Singh, V.K. & Elomaa, O. et al. (2014), Lubricating Properties of Silica/Graphene Oxide Composite Powders, Carbon 79, pp. 227–235..
5. Jaatinen et al. (2014), FZG-tests, Wind Energy, to be submitted.

Number of publications: 11
Number of Master's Theses: 2

Networks and international co-operation

Related to international collaboration, joint seminars were arranged with Kanagawa Industrial Technology Center in Japan and with Argon National Laboratory in USA. Advanced carbon nanomaterials optimized for project use were provided by Dr Olga Shenderova, Head of the Nanodiamond Laboratory, International Technology Center, USA and purchased from Dr. Vesa Myllymäki, Carbodeon Ltd Oy, Finland. Joint publications concerning carbon nanoparticles in liquid lubrication were achieved together with these scientists and their expertise used for test planning and result analysis. Added value: more profound understanding of the effect of nanocarbons in lubrication.

Applications and impact

The results can be used in all components subject to high-load, lubricated mechanical contacts. This enables energy savings and lighter designs for more economical, sustainable and reliable components such as gears. The methods developed in this project will be further optimized and used by the industrial partner.

The results in carbon-based novel lubricant additives are foreseen to impact in novel lubricant concepts within 10 years.

Industrial partner comment: Moventas

30% higher torque on gear tooth surface achieved – efficiency and weight savings

The surface finishing methods used in the project resulted in reduction of overall weight of the wind turbine gear mass, 30% higher torque on gear tooth surface and better torque density. These enabled increased wind turbine gear efficiency.

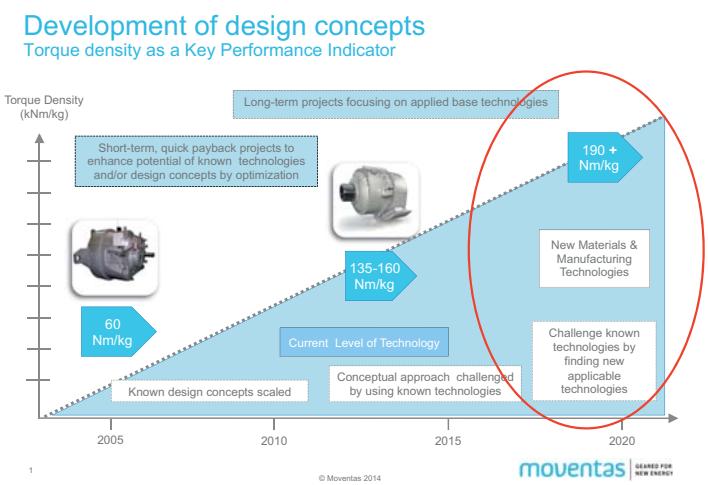
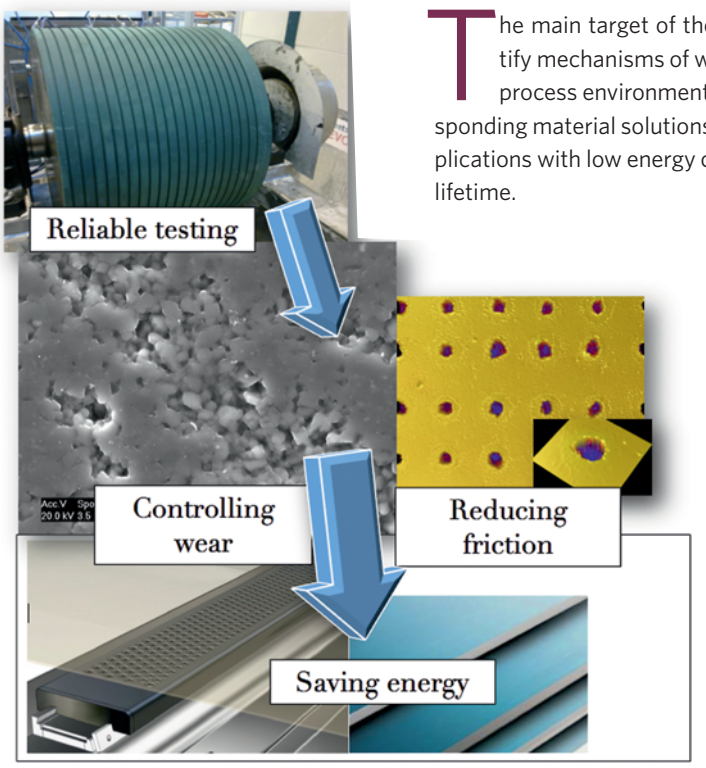


Figure 1. **Torque density development in wind mill gearboxes**

PROJECT NAME
P4 Friction and Energy

LOPRO

Low Friction in Process Environment



The main target of the project was to identify mechanisms of wear and friction in the process environment and to develop corresponding material solutions to bring potential applications with low energy consumption and long lifetime.

Valmet TAMPERE UNIVERSITY OF TECHNOLOGY

1) Threshold values for material properties

Connections between material properties and severity of wear were studied using a high-velocity sliding test rig. It was found that an optimal combination of hardness and fracture toughness is necessary for a material to resist wear in sliding velocities in and above the region of 1000 m/min, which is the sliding velocity range of a modern paper machine. Failing to meet the requirements leads to transition from mild to severe wear mode. Figure 1 summarises these findings.

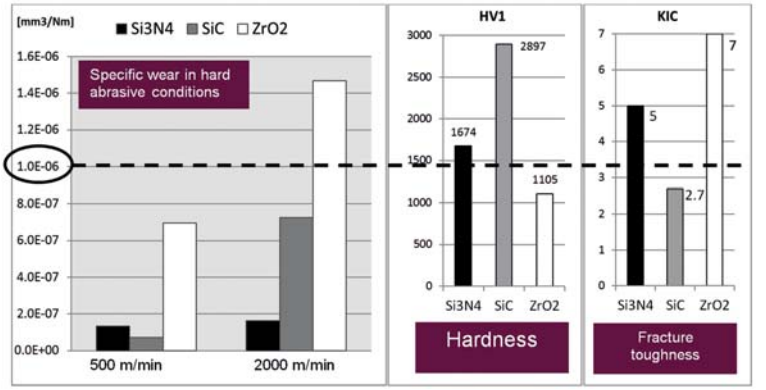


Figure 1. **Specific wear values and mechanical properties of three ceramics**

A combination of hardness and toughness is essential for wear resistance

Studies conducted at TUT show that the required properties can be achieved with a nanocomposite structure. Introducing nano-sized nickel particles into alumina ceramic improved the fracture toughness by 16% with no decrease in hardness.

2) Controlling friction with surface topography

An investigation was made into the potential of surface topographies for reducing friction in wet high-speed sliding. The effect of surface topography on friction was first observed with hot rolled stainless steel bars. Evolution of friction (see Figure 2) due to wear was observed in the speed range of roughly 6–8 m/s, which points to the original topography being better in terms of friction.

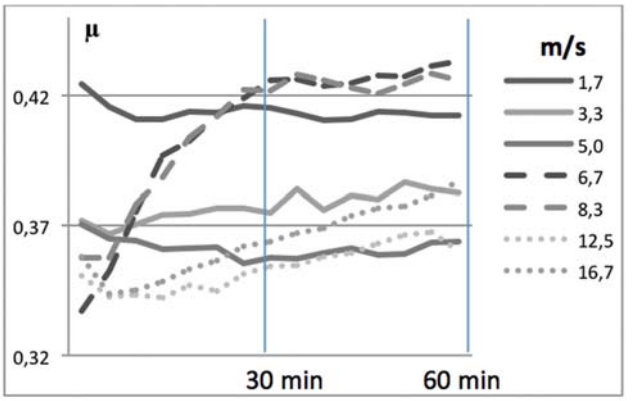


Figure 2. **Evolution of friction for AISI 316L during a 60 min test run**

Laser technology has become more controllable and affordable in recent years. Pulsed fibre laser was the method of choice for producing the required topographies on hard materials. Silicon nitride was chosen due to its wear resistance, since it was important to measure the effects of a surface structure with minimal wear. The hypothesis was either for the dimples to act as reservoirs for lubricant or to collect wear debris and hard particles during sliding. Both of these mechanisms provide lower friction and wear, yielding better efficiency if correctly applied to a process environment. A multi-pulse approach to making dimples was taken, though a single pulse method was also tested. Using multiple pulses per dimple (i.e. drilling) brought better controllability over the process and also produced more satisfactory geometries. This of course hurts the scalability of the process on larger surfaces. The processing time for a small area increased from seconds to minutes when moved from single pulse to drilling.

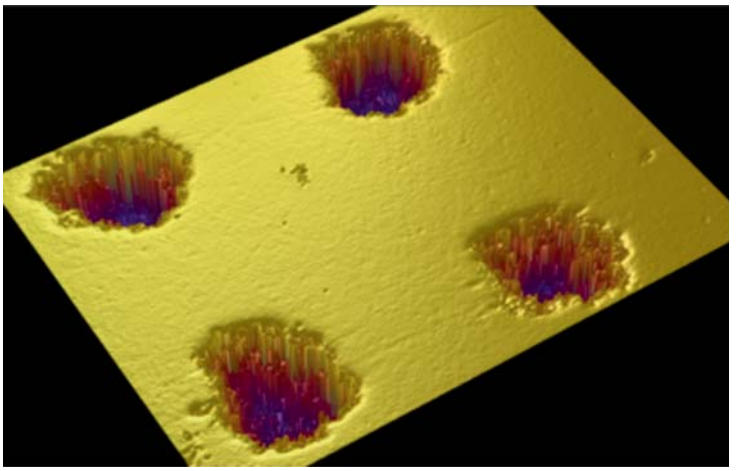


Figure 3. **Dimple topography on silicon nitride ceramic**

The effects of surface texturing on friction in our test environment (see Figure 4b) were significantly different from those observed in other, more conventional tribological tests carried out at nCATS in Southampton (see Figure 4a). In wet high-speed sliding, the overall added roughness of a surface by laser treatment seems to have more of an impact on friction than a specific topography, since the single pulsed surface also provided lower friction than a polished equivalent. Overall, however, a well processed surface topography showed the lowest friction. Adjusting the wetting properties of laser-treated surfaces did not produce additional value, as presented in Figure 4a.

Friction and wear reduction by optimal topography

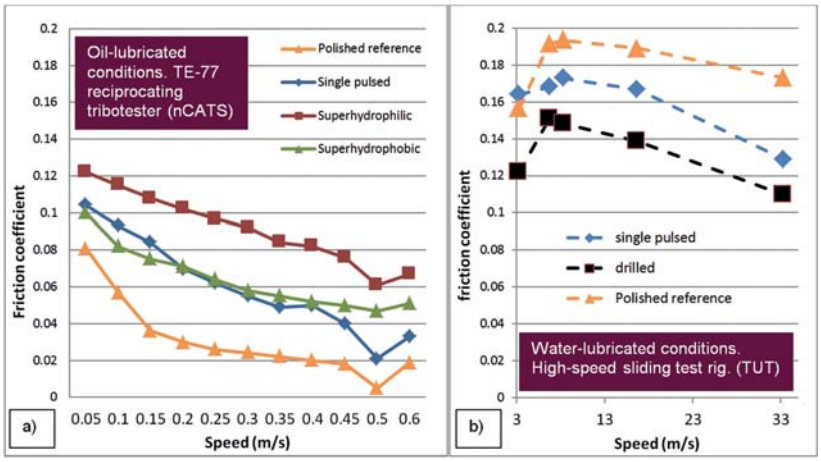


Figure 4. **Friction data of structured surfaces in different conditions**

PROJECT NAME

P4 Friction and Energy

LOPRO

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PROJECT DURATION

2010 – 2014

PROJECT VALUE (EUR)

1.234 MILLION

Performance from understanding of high-velocity sliding

Low Friction in Process Environment

Main targets & motivation

Introduction: Sliding velocities in modern paper machines are very high; 1000 to 2000 m/min (~16.7 to 33.3 m/s), a range rarely covered in tribological research. Because of this, the current understanding of friction and wear in these conditions has to be revised. The two characteristic attributes of the application are high sliding velocity and the presence of process fluids.

Motivation: Reducing friction and wear in key contacts of the paper making process would bring significant savings in the form of longer lifespan of components and energy savings.

Objectives: One objective was to identify the relevant phenomena behind friction and wear behaviour of the commonly used wear-resistant materials in the paper machine environment. The results can be used to guide material development. Another objective was to find ways of reducing friction in these conditions by state-of-the-art laser processing.

The novelty and added value aspect of this work is largely due to the rarely ventured research field of high-velocity sliding. Introducing paper machine conditions to compact test equipment has never been reported. Friction reduction by laser-structured topographies is widely studied for several tribological systems. Hypotheses for lowering friction by this method seem promising.

Combining proper material properties provides energy savings

The main research problem of this study was to identify the effects of high sliding velocity in wet conditions on mechanisms of friction and wear. Both wear and friction are known to be sensitive to changes in loading (velocity) and chemistry (process fluids).

Results

- A viable testing method was produced for high-velocity sliding in water-containing environments. The equipment can be used to produce reliable wear data, friction measurements and the combination of the two. Low-cost tests can be run for experimental surfaces and materials in conditions fairly comparable to the real process in terms of sliding velocity (up to 2500 m/min) and process fluids. Wear process can be greatly accelerated by adjusting slurry composition or minimised by using plain water.
- Sliding velocity has a significant effect on what material properties appear essential for achieving low wear. We established that in order to perform well in water-lubricated high-velocity sliding conditions there are boundary requirements for hardness and fracture toughness of a material.
- The impact of a material's toughness was amplified as sliding velocities in tests increased. This phenomenon was observed for thermally sprayed coatings and bulk ceramics.
- The processing of low-cost alumina-nickel nanocomposites was demonstrated successfully using pulsed electric current sintering (PECS).
- Nickel nanoparticles increased the toughness of alumina ceramic by 16%.
- A surface polished to minimum average roughness (Ra) was found not to be the best alternative for low friction in a wet high-speed test environment. Surfaces with a certain kind of topography produced lower friction. Tests conducted with a traditional tribometer produced contradicting results, suggesting that the mechanisms affecting the friction of structured surfaces in these two methods differ significantly.
- The exact geometry of a surface topography on silicon nitride ceramic became less relevant as sliding velocity was increased. Even sub-optimally processed topographies produced lower friction than polished equivalents in very high sliding velocities. A well processed surface produced low friction overall.
- Improved coating material solutions to be used in different sliding contacts of paper machine components.

Key publications

1. Ismailov, A. & Levänen, E. (2013), High-speed wear testing of selected ceramics in abrasive slurry, IOP Conf. Ser. Mater. Sci. Eng., Vol. 47.
2. Kannisto, E.J., Cura, E., Levänen, E. & Hannula, S-P. (2013), Mechanical properties of Alumina-based Nanocomposites, Key Engineering Materials, Vol. 527, pp 101–106.

3. Kannisto, E.J. & Levänen, E. (2012), Geometrical Model to Evaluate the Lower Boundary of Nanoparticle Size in Ceramic/Metal Nanocomposites Produced By Thermolysis, Journal of the Georgian Ceramicists' Association Vol. 28. No. 2, pp. 24–29.
4. Ismailov, A. & Levänen, E. (2013), The effect of high sliding speed on friction in aqueous conditions, Book of proceedings: World Tribology Congress, Torino, Italy.
5. Ismailov, A., Kumpulainen, T., Vihinen, J. & Levänen, E. (2014), High-speed sliding friction of laser-textured silicon nitride in water against rubber, 28th International Conference on Surface Modification Technologies, 16–18 June, 2014, Tampere University of Technology, Tampere, Finland.

Number of publications: 11
Number of Doctoral Theses: 2 in progress
(1 in the TUT Graduate School)
Number of Master's Theses: 3
Number of patent applications/patents: 1

Networks and international co-operation

Laser-structured silicon nitride surfaces were tested at nCATS in Southampton. The results of this work provided a good reference for the tests conducted in Finland. The collaboration is ongoing in the form of further testing of laser-structured surfaces.

Applications and impact

Utilisation of results (applications): wear-resistant, low-friction surfaces all over paper machinery. Especially with water-removal elements to ensure simple structures with long life time, hard-tipped doctor/application blades to ensure long life time with less friction, wear-resistant application rods and wear-resistant roll coatings and covers.

Commercialisation of results: evident potential as spin-off from the results, partly already advanced to ready products.

Significance of the results achieved: important knowledge and material screening for further product development and commercialisation by Valmet Technologies Oy and Kraftcer Ltd.

High Friction Low-Wear Contacts

New international benchmark for modelling of wire-rope-to-sheave contacts

A novel finite element model was developed for the contact pressure, friction, fatigue and wear conditions in wire-rope-to-sheave contacts of a rope drive (Figure 1). The model is based on a developed and implemented numerical library for generating three-dimensional finite element models of wire-rope-to-sheave contact in full detail, carrying out the nonlinear contact analyses and applying micromechanically founded damage models for component lifetime. This is the most advanced and largest model in its category so far developed, worldwide.

Wire-rope-to-sheave contacts have proven to be a troublesome engineering problem, primarily because of complexities associated with the wire rope and its behaviour. Analytical means provide rough and rudimentary estimates of wire rope response, but the simplifications are grave against the actual behaviour and geometric details of the wire ropes.

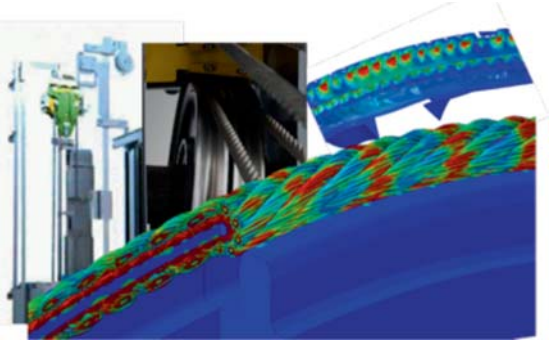

Figure 1. **New high-friction and low-wear material solutions resulted in 35% better frictional traction and orders of magnitude of lower wear for the sheave-to-wire-rope contact in elevators and cranes**

The new model solves the problems related to the high complexity of the internal contacts between wires and strands, and furthermore solves the complicated and analytically nearly impossible problems when the wire rope is in contact with an actual component, such as a sheave. As a solution, numerical means were used to come up with a consistent formulation and numerical layout for the problem, and to tackle issues in convergence response and computational cost in order to obtain actually exploitable results.

An example of analysis results demonstrating the ability of the model to resolve the contact response is presented in Figure 1. The results were used as an input for the development of a lifetime-estimation engineering tool.

Improved understanding of basic wear and friction mechanisms

The contact between the sheave and the wire rope consists of a rolling motion with low slipping, and sliding perpendicular to rolling. The contact is boundary-lubricated by paraffinic Vaseline. The wear process of nodular cast iron sheaves in normal in-service conditions is dominated by macro- and micro-level *plastic-flow-induced ductile fracturing* (see Figure 2). The sliding component of the contact motion induces plastic deformation which, in joint effect with the rolling motion, causes subsurface crack initiation at the interface of the metal matrix and graphite nodules. The cracks propagate either internodularly or towards the wear surface.
Cracks extending to the wear surface enable increased plastic deformation, which results in formation of metallic deformation tongues. Material removal proceeds by spalling of small pieces of the deformation tongues at the low contact pressure levels in the elevator sheaves, or of entire deformation tongues at the increased contact pressures in the hoist machineries.

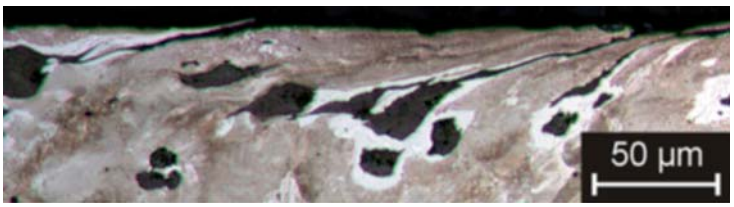

Figure 2. **Cross-section of a worn invert sheave presenting the plastic-flow-induced ductile fracturing**

The nodule count notably affects the wear behaviour of ductile cast irons. Resistance against rolling contact fatigue and tribochemical sliding wear is increased by increased nodule count. Conversely, increased nodule count decreases wear resistance in severe sliding contacts. The graphite nodule size and count can have a significant effect on the friction behaviour of the unlubricated contact. Graphite present in the contact acts as a solid lubricant and may result in reduced friction.

Unique engineering tool handles relevant complex phenomena – key for right design and lifetime prediction

A unique material-modelling-based engineering tool

An engineering tool based on computational modelling was developed for design evaluation of wear and low-cycle fatigue. The approach was founded on the evaluation and development of lifetime estimation means for low-cycle fatigue and cumulative wear as the result of repeated wire-rope-to-sheave contacts. The low-cycle fatigue evaluation concerns failure of individual wires of the rope and its strands, thus resulting ultimately in the total failure of the rope, while the wear analysis concerns material loss from the sheave surface as a result of the tribological wire-rope-to-sheave contact.
On the basis of tribological analysis and failed component characterisation efforts, failure mechanisms critical to component life were identified and lifetime estimation procedures developed, demonstrated and verified. Experimental efforts complement the modelling to determine the required model inputs, as well as provide verification.
The full-detail finite element models of the wire-rope-to-sheave contact provided the basis for evaluating the criteria for fatigue and wear, as well as transferability and exploitability of various results and methods developed during the project. The methodologies were implemented in a software solution based on a graphical user interface, exploiting the numerical methods and both numerical and experimental results obtained during the project. The methodology developed is extensible and provides the basic functionalities for lifetime estimation of complex wire-rope-to-sheave contacts.

Friction, wear and lifetime of four material groups investigated

The tribological performance of materials representing four sheave material groups was investigated experimentally. The material groups were non-hardened cast iron, hardened ductile cast iron, commercial thermal spray coatings and newly developed thermal spray coatings.

The results were compared to the reference material representing today's commercial material commonly in use (see Figure 3). The hardened ductile cast iron represented a novel advanced development of the cast iron sheave solution, while the thermal spray coatings repre-

sented a completely new material group for this application of which there was no previous experience. The countersurface was a standard steel wire rope.

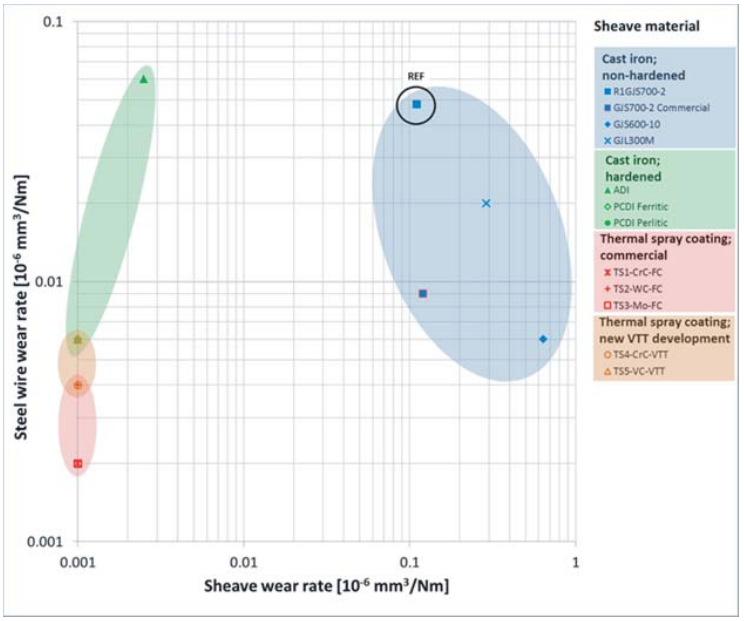

Figure 3. **Sheave wear vs. wire rope wear**

The investigation showed that new material solutions for the elevator sheave material can increase the desired friction in the wire rope contact by 35%, while at the same time reducing the sheave wear rate to only one per cent, and the wear rate at the wires of the rope by 80%. The most promising new material solutions were a commercial CrC-25NiCr thermal-spray-coated sheave, a newly developed VTT CrC-Fe-Cr thermal spray coating applied on sheave grooves, and a partially chilled ductile cast iron sheave.

PROJECT NAME

P4 Friction and Energy

HICON

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PROJECT DURATION

2010 – 2014

PROJECT VALUE (EUR)

2.126 MILLION

New robust material solutions for elevator and crane lifting mechanisms

High Friction Low-Wear Contacts

Main targets & motivation

Smooth people flow and transport of goods in public, commercial and private buildings becomes even more important as the size and capacity of buildings and infrastructure increases. Continuous economical and standard improvements enable smart and more efficient solutions. At the same time emphasis is placed on sustainability and low energy consumption in urbanisation. Reduction of moving accelerated mass and reduced ecological footprint can help to gain a strong marketing position..

Globally, there are approximately 12 million operating elevators – distributed as 47% in Europe- Middle East, 10% in North America and 39% in Asia-Pacific – in need to be modernised with new eco-efficient applications. Industrial cranes have a crucial role in the logistics of goods in harbors, construction sites and factories. High friction and low wear traction in the wire rope to sheave contact improves safety, enables savings through weight reduction and is a step to future smart solutions in this field of industry.

The aim in this project was to create a platform of deeper understanding of high-friction and low-wear tribological contacts appearing typically in vertical logistics, such as in wire-rope-to-sheave or wheel systems in elevators, cranes and similar. The aim was to find new designs and new tribomaterial solutions that result in longer lifetime, improved efficiency, safety, reduced energy consumption and sustainable applications.

Results

Advanced material solutions give safe friction and radically reduced wear

A novel integrated research methodology was developed by combining diagnostics of worn components used in real conditions, analysis of tribological friction and wear mechanisms, laboratory and real component testing, computational material modelling and simulation and, based on this, the development of an **engineering design tool for optimal sheave and wire rope design**.

The laboratory-scale basic tribological measurements showed that state-of-the-art material solutions can be improved greatly by advanced, hardened, partially chilled ductile cast iron, and still further by composite structured thermal spray coatings applied on the sheave groove surface. Microscale structural analysis showed that the crucial and complex wear mechanism involved is dominated by macro- and microlevel plastic-flow-induced ductile fracturing.

The laboratory-scale twin-disc test principle was re-developed to correlate very well with the contact conditions in rope drives in real use. The investigations showed that new material solutions for the elevator sheave material **can increase the desired friction force in the wire-rope-to-groove contact by 35%, at the same time reducing the sheave wear rate to only one per cent, and the wear rate of the wire rope surface by 80%.** The most promising new material solutions turned out to be a commercial CrC-25NiCr thermal-spray-coated sheave groove coating, a newly developed VTT CrC-FeCr thermal spray coating for a sheave groove, and a partially chilled ductile cast iron sheave material.

An engineering tool for life estimation of wire-rope-to-sheave contacts, the HiconLife tool, was developed and demonstrated during the project. The solution consists of a graphical user interface and two analysis packages, one for the evaluation of sheave wear and one for the evaluation of low-cycle fatigue of the wire rope. A software library for finite element analysis of wire-rope-to-sheave contacts was developed. A Rainflow methodology was implemented for analysis of low-cycle fatigue. A solution for data mining of results databases was introduced for exploitation in, and interfacing to, engineering analyses.

Key publications

1. Holmberg, K. & Laukkanen, A. (2012), Wear models. In: Bruce R (ed.) Handbook on Lubrication and Tribology, Vol. II Theory and Design, 2nd edition, Chapter 13, CRC Press, New York, USA.
2. Oksanen, V., Andersson, P., Valtonen, K., Holmberg, K. & Kuokkala, V-T. (2012), Wear analysis of rollers of nodular cast iron in contact with wire ropes. Proc. 15th Nordic Symp. on Tribology, Trondheim, Norway, 12–15 June 2012.

3. Oksanen, V., Andersson, P., Valtonen, K., Holmberg, K. & Kuokkala, V-T. (2013), Characterization of the wear of nodular cast iron rollers in contact with wire ropes. Wear 308, pp. 199–205.
4. Waudby, R., Andersson, P. & Holmberg, K. (2013), Low-speed sliding tests with nodular cast iron in contact with steel wire and a diamond tip. Tribology International, Vol. 65, pp. 171–176.
5. Waudby, R., Andersson, P. & Holmberg, K. (2013), Scratch testing of nodular cast iron with diamond and steel wire tips. Proc. 39th Leeds-Lyon Symp. on Tribology, Lyon, France, 4–6 September 2013.

Number of publications: 7
Number of Master's Theses: 5

Networking and international co-operation

The project resulted in a strong national networking of the key players in Finland in elevator and crane tribological design in and in engineering development and research. It included product development and manufacturing expertise from industry, and material science, testing and modelling experience from research institute and university.
The tribological testing was partly carried out under the European project "Metrology to assess the durability and function of engineered surfaces", including partners from seven European countries and the Centre for Technology and Accreditation (MIKES) as responsible partner from Finland.

Applications & impact

The project resulted in new understanding of the wear mechanisms of reference materials in use in elevators for the past 30 years. Comparisons of the results from component-level testers and twin-disc test equipment brought improvements in the predictability of the groove wear rate under different operational conditions. This is very important for future lifetime estimations in industrial R&D projects.

New understanding of the wear mechanisms of reference materials used in elevators for the past 30 years

The new engineering tool opens up a possibility for quick twin-disc testing of new material pairs, and extends the analysis of groove lifetime prediction on the system level. The project found two promising new wear-resistant materials which have been taken into further assessment on an industrial product development level for the analysis of their commercial potential and for endurance testing.

Experimental studies and modelling hand-in-hand

For crane applications, the project increased the understanding of phenomena in wire-rope-to-rope-sheave contacts, and inside wire ropes. The engineering tool will be used for estimating factors needed when estimating the lifetimes of wire rope and sheave combinations. An accelerated rope testing method was developed and verified successfully. The results will be used in new engineering solutions for future cranes.

From the material sub-supplier point of view, participating in a research project among customers turned out to be very beneficial. Strengthening of relations and gaining knowledge of industry development trends is a key factor for success. Going first-hand from scientific research to the resulting product development is a great benefit. Results and the analogy of wear and friction will be used in several industrial applications. Participating in this project has increased the company´s intellectual equity and will most probably increase new sales potential through improved applications.

PROJECT NAME
P4 Friction and Energy

LOHYD

Low Friction in Hydraulics

Need to replace hard chrome

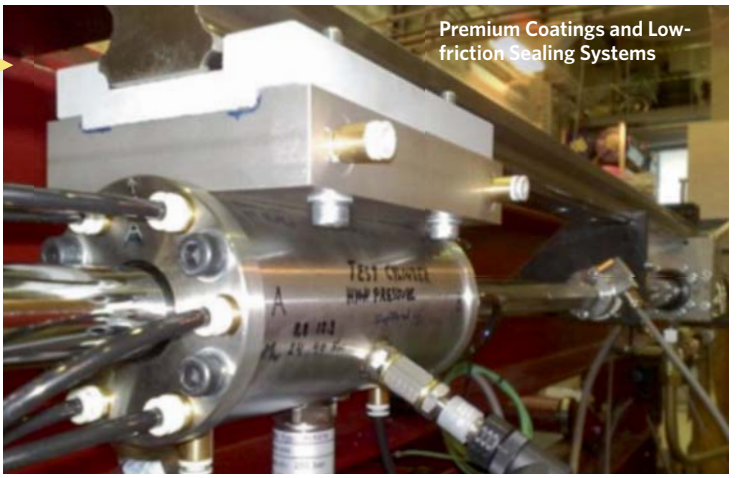


Figure 1. **Test rig for validation of piston rod sealing systems**

Background

- The motivation for the research was to find alternatives for hard chrome plating of hydraulic cylinder piston rods.
- Coated surfaces for technical applications are often made by electroplating with chromium. The production process can, however, release hexavalent chromium, which is considered to be a biologically harmful substance.
- By using a different coating method, it would be possible to deposit materials containing non-risk chromium compounds, or materials altogether chrome-free. In addition, new hard and dense coating materials could bring clear improvement to the wear and corrosion resistance of hard chrome.

Targets

- To develop a high-deposition rate procedure for coating of piston rods.
- Requirements for the rod surface are:
  - high hardness
  - good corrosion resistance
  - to function as a low-friction sealing surface.
- To develop a reliable and low-friction sealing system to operate with the new coating and validate the sealing in realistic functional tests.

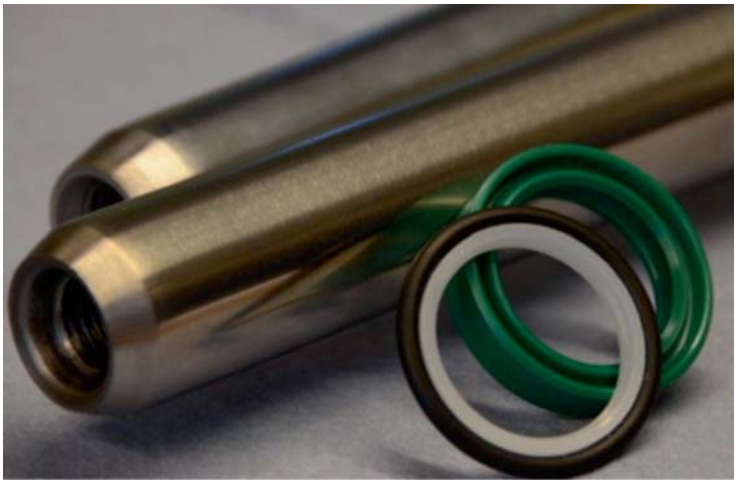


Figure 2. **Coated piston rods and rod seals**

Research topics

- Review of suitable state-of-the-art coating methods.
- Produce test samples with the most promising coating process and with different surface-finishing techniques.
- Design and build test rigs for piston rod sealing validation for both water and hydraulic oil as a pressure medium.
- Perform validation tests with piston rods featuring new hard coating and different sealing solutions; measure friction force and leakage in long-term tests.
- Perform metal fatigue tests with non-coated piston rod base material as well as with coated material. Several S/N curves were produced to assess the effect of manufacturing phases on fatigue performance.

Thermal spraying of chromium carbide combines productivity and performance

Results

1) New coating procedure for piston rods (Nurmi Hydraulics/Fincoat)

Thermal spraying was found to be the most promising coating method for piston rods. A range of high-quality coating materials can be deposited at a high rate suitable for even very large hydraulic cylinder piston rods. By careful selection of process parameters and combustion type, a dense surface layer can be created providing good wear and corrosion protection.

For the functional tests, the project selected chromium carbide as the coating material. This coating performed well in tests with different sealing solutions and with hydraulic oil as a pressure medium.

Figure 2 shows a thermally sprayed piston rod (in the middle) and a chrome-plated rod (in the background) together with rod seal types used in the test programme. Figure 3 shows the thermal spraying process.

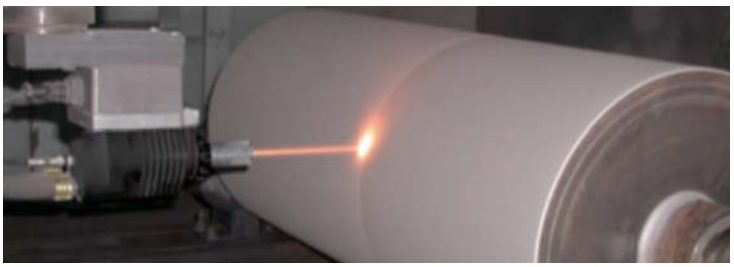


Figure 3. **Thermal spraying (Uniquecoat Technologies LLC; Representative in Finland: Fincoat Oy)**

The finishing of the coated surface was done by grinding and polishing with very hard abrasives.

Production of a good sealing surface involves developing a process that results in a surface smooth enough to avoid excess seal wear, but still possessing roughness, promoting lubrication of the contact between the seal and the piston rod (Figure 4).

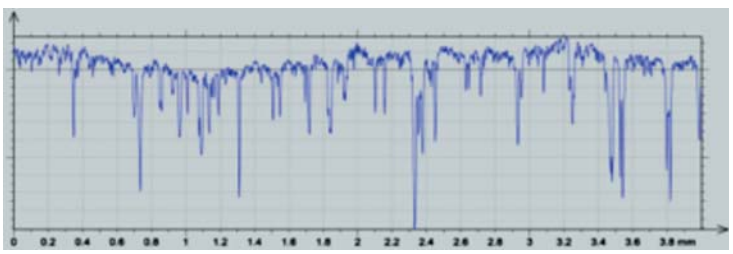


Figure 4. **Example of tailored surface finish of the new coating**

In addition, the new coating has passed tests concerning coating hardness and scratch resistance, as well as corrosion tests (500 h salt spray).

2) Validation test results (Aalto ENG)

Two different test rig setups were built, one for testing with hydraulic oil (Figure 1) and the other for testing with water. In the tests with oil, different coated piston rods were run continually for five days (200,000 piston strokes, sliding distance approximately 80 km) at 160 bar and a nominal sliding speed of 200 mm/s. Figure 5 shows a typical friction force curve measured between two reversals in the cyclic test. In Figure 6, the performance of two sealing systems is shown. System 1 is a single-seal, double-seal lip solution. System 2 was a tandem seal solution.

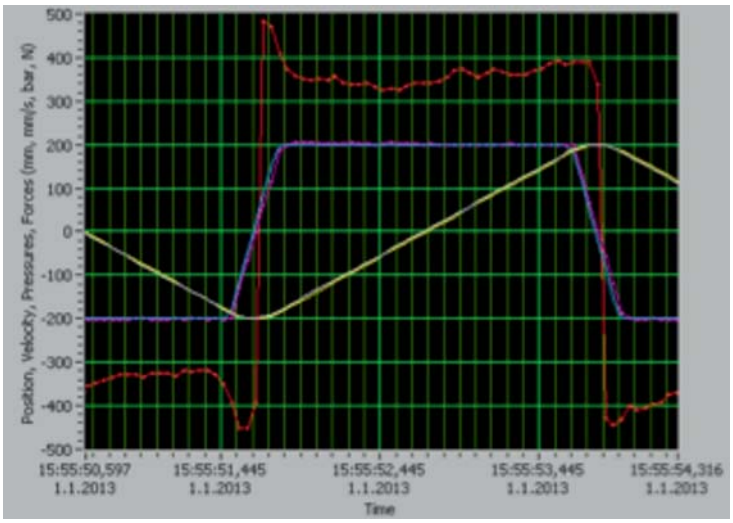


Figure 5. **Piston rod motion cycle (purple = velocity, yellow = position) and friction force (red), measured during the test**

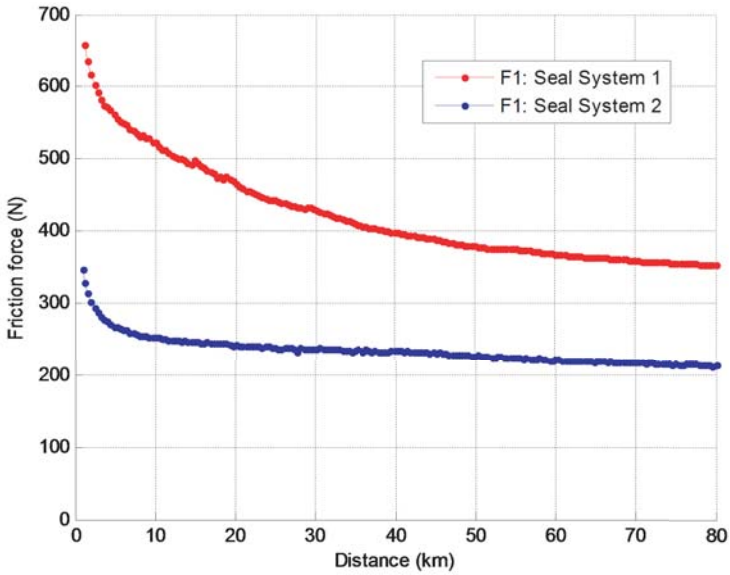


Figure 6. **Mid-stroke average friction force vs. sliding distance: low friction achieved with tandem sealing**

Tandem sealing to reduce friction force

In Figure 6 it can be seen that by using Seal System 2 the friction force can be dramatically reduced, while the force also settles much more rapidly.

3) Fatigue tests (Aalto ENG/TU Liberec)

As part of a PhD project, a study was made of the effect of various machining phases and coating on fatigue performance of the piston rod steel. Figure 7 shows S/N curves indicating the increase in fatigue performance due to carefully produced chromium carbide coating. This thermal spray coating was made by VTT. The lowest curve is for turned structural steel specimens (Ra 1.6 µm). The highest curve is for chromium carbide coated specimens having a polished surface (Ra 0.15 µm) representing sliding surface finish of hydraulic cylinders. If the turned surface was only polished to the same surface finish (middle curve), the fatigue performance improvement was not as large.

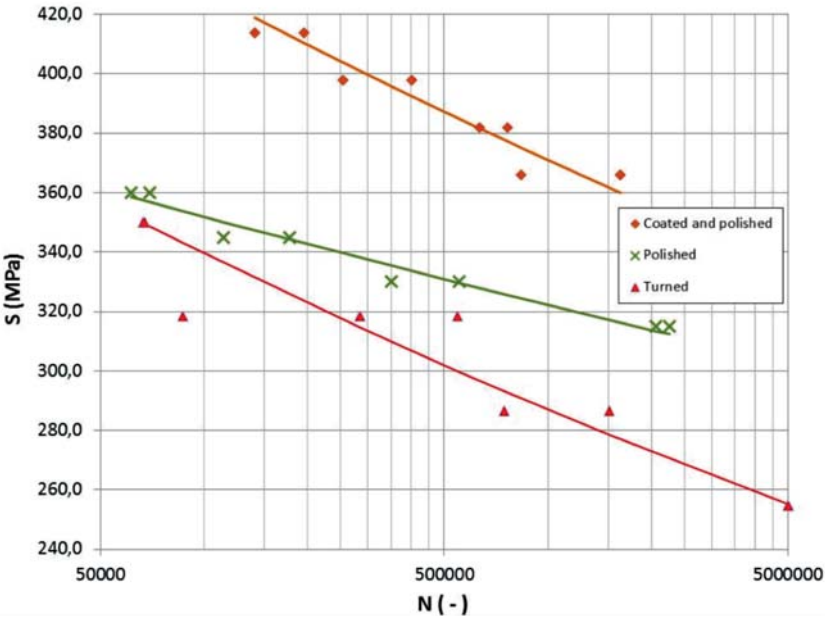


Figure 7. **Fatigue test results**

PROJECT NAME

P4 Friction and Energy

LOHYD

CONTACT PERSON	PARTICIPANTS (ORGANISATIONS)	PROJECT DURATION	PROJECT VALUE (EUR)
JUHA ELONEN NURMI HYDRAULICS OY **OLOF CALONIUS** AALTO UNIVERSITY	**AALTO UNIVERSITY** **NURMI HYDRAULICS OY**	**2010 – 2013**	**0.187 MILLION**

Low Friction in Hydraulics

Main targets & motivation

- To find new cost optimal coating materials to replace hard chrome plating of hydraulic cylinder piston rods. Hard chrome plating is widely used, but the coating process releases hexavalent chromium, which is biologically harmful. In demanding operating conditions, there is also a need for new coating materials with better wear and corrosion resistance.
- To find reliable sealing solutions for the new coatings – targets are low friction and no leakage. Hard coatings can cause increased seal wear and friction, unless an adequate surface finish is given to the coating and a suitable seal material adopted. Any newfound combinations of coating material and sealing solution must be validated in high-pressure functional tests.
- Today, when better coating than hard chrome is needed, the piston rods must be shipped abroad for coating and surface finishing. This study aims at developing high-quality coating that can be produced domestically without long lead time.

Thermally sprayed chromium carbide coatings – sustainable, wear- and corrosion-resistant

Results

- A good alternative to hard chrome coating was found: thermally sprayed chromium carbide using the HVAF process. Here the chrome needed for corrosion protection is not present in the form of harmful Cr6+.
- While the efficient HVAF process has been used for large products in heavy industrial machinery, it was now successfully adopted for piston rods.
- HVAF-coated piston rods are more wear-resistant than chrome-coated rods, and their corrosion resistance is equivalent or better, depending on the thickness of the coating.

- Low-friction and non-leaking sealing was achieved using tandem seals in a suitable combination of low-friction and low-leakage materials.
- The fatigue performance of steel (S/N curves) used to produce piston rods was determined in different stages of production, as well as in the final state, coated by thermally sprayed chromium carbide and ground to sealing surface finish.

Key publications

1. Čuban J., Calonius O., Pietola M. & Jersák J., (2011), Fatigue life and surface integrity measurements of EN S355J2 steel used in hydraulic components, Manufacturing Technology, Vol. 11, No 11, Dec 2011.
2. Calonius, O. (2013), Sealing Surfaces in Hydraulic Cylinders – Sealing Mechanism and Surface Requirements, DEMAPP project report.
3. Eskonen H., (2013) Test Rig for Research on Hydraulic Cylinder Piston Rod Seal Friction, B.Sc. Thesis (in Finnish), Aalto University.
4. Calonius O. (2013), Validation testing of sealing solutions for coated hydraulic cylinder piston rods, DEMAPP project report.
5. Vepsäläinen, J. (2013), Friction force of hydraulic cylinder seals, B.Sc. Thesis (in Finnish), Aalto University.

Number of publications: 6
Number of Bachelor's Theses: 2

Networks and international co-operation

The new HVAF coating process for piston rods is the result of co-operation between Nurmi Hydraulics and its subcontractor Fincoat.

Thremally sprayed coatings for fatigue performance studies were produced by VTT.

A doctoral student from the Czech Republic, Technical University of Liberec, was working as visiting researcher at Aalto University in 2011, focusing on fatigue issues.

Applications & impact

- Piston rods coated with the new process have already been introduced in pilot products for challenging applications such as hydraulic cylinders in wave energy converters.
- The new coating process, including surface finishing techniques, and the new hard coating materials are an important addition to the premium product range. In products for challenging applications, the dependency on foreign subcontractors and the time-consuming logistics in-between production phases can be avoided.

Friction Energy and Economic Impact

From micro-level tribocontacts to global scale

A novel methodology was developed in the project to calculate friction on several scale levels, from global energy to overcome friction, to friction in microlevel tribological contacts, (see Figure 1). For each of the three cases, the methodology included an analysis of global energy consumption, distribution of friction and energy losses in defined average machinery or vehicle, operational cycle effects, tribocontact frictional levels today and in future, and global frictional losses and potential savings.

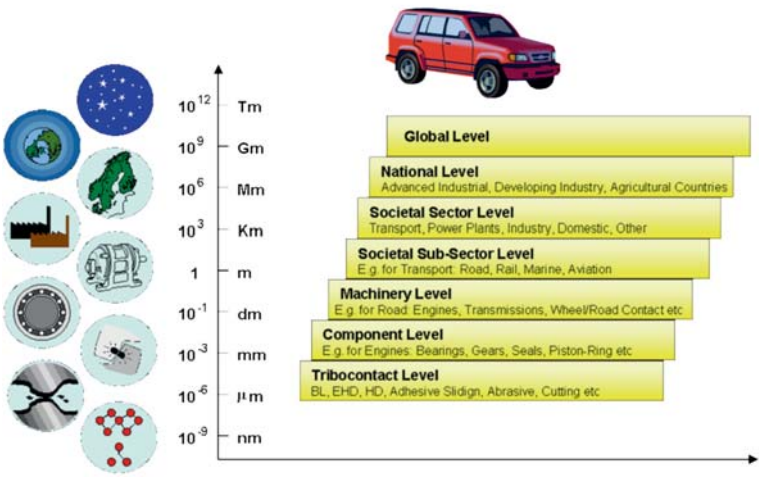


Figure 1. **Scale levels for calculating friction losses in passenger cars, from global energy to overcome friction, to friction in microlevel tribocontacts**

Case 1. Passenger cars

The study showed that in passenger cars, one-third of the fuel energy is used to overcome friction in the engine, transmission, tyres, and brakes, as shown in Figure 2. The direct frictional losses, with braking

friction excluded, are 28% of the fuel energy. In total, 21.5% of the fuel energy is used to move the car. Worldwide, 208 billion litres of fuel were used in 2009 to overcome friction in passenger cars. Reductions in frictional losses will lead to a threefold improvement in fuel economy, as it will also reduce both the exhaust and cooling losses in the same ratio.

Globally, one passenger car uses on average 340 litres of fuel per year to overcome friction, which would cost 510 euros according to the average European gas price in 2011, and corresponds to an average driving distance of 13,000 km/a. By taking advantage of new technology for friction reduction in passenger cars, fuel consumption could be reduced by 18% in the short term (5 to 10 years). This would equal worldwide economic savings of 174 billion euros, fuel savings of 117 billion litres, and CO_2 emission reduction of 290 million tonnes. The corresponding savings could be up to 61% in the long term (15 to 25 years). The friction-related energy losses in an electric car are estimated to be only about half those of an internal combustion passenger car.

18% of energy consumption in transport can be saved using new tribological technologies

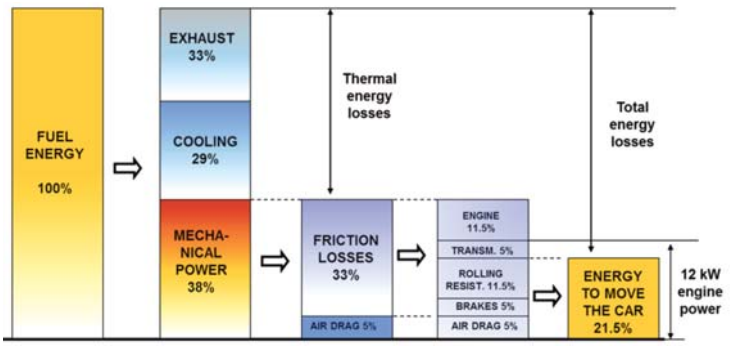


Figure 2. **Breakdown of passenger car energy consumption**

Case 2. Heavy duty vehicles

The study on **heavy duty vehicles** focused on four types: single-unit trucks, semi-trailer trucks, city buses and coaches. In heavy duty vehicles, 33% of the fuel energy is used to overcome friction in the engine, transmission, tyres, auxiliary equipment, and brakes. The parasitic frictional losses, with braking friction excluded, are 26% of the fuel energy. In total, 34% of the fuel energy is used to move the vehicle. Worldwide, 180 billion litres of fuel were used in 2012 to overcome friction in heavy duty vehicles. A reduction in friction results in a 2.5 times improvement in fuel economy, as exhaust and cooling losses are also reduced.

Globally a single-unit truck uses on average 1,500 litres of diesel fuel per year to overcome friction losses; a truck and trailer combination, 12,500 litres; a city bus, 12,700 litres; and a coach, 7,100 litres. By taking advantage of new technology for friction reduction in heavy duty vehicles, friction losses could be reduced by 14% in the short term (4 to 8 years) and by 37% in the long term (8 to 12 years). In the short term, this would equal annual worldwide savings of 105 billion euros, 75 billion litres of diesel fuel, and a CO_2 emission reduction of 200 million tonnes.

Hybridisation and electrification are only expected to penetrate certain niches of the heavy-duty vehicle sector. In the case of city buses and delivery trucks, hybridisation can cut fuel consumption by 25% to 30%, but there is little to gain in the case of coaches and long-haul trucks. Downsizing the internal combustion engine and using recuperative braking energy can also reduce friction losses. Electrification is best suited to city buses and delivery trucks. The energy used to overcome friction in electric vehicles is estimated to be less than half of that of conventional diesel vehicles.

Potential new remedies for reducing friction in road vehicles include the use of advanced low-friction coatings and surface texturing technology on sliding, rolling, and reciprocating engine and transmission components, new low-viscosity and low-shear lubricants and additives, and new tyre designs that reduce rolling friction.

Figure 3 shows the level of friction in an average heavy duty vehicle in use today in the various friction contacts (Truck & bus 2000), the lower level reported in the best new vehicles today (Truck & bus 2013), the lowest levels reported in research laboratories so far (Laboratory 2013) and levels foresighted to be reached by future research and development work (Truck & bus 2015).

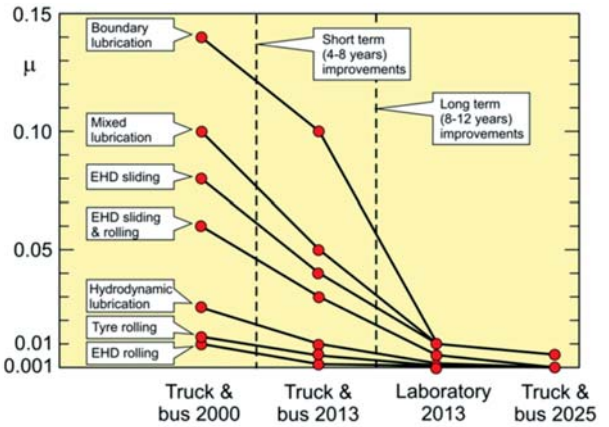


Figure 3. **Trends in coefficient-of-friction levels for different lubrication mechanisms and rolling friction and for four categories of vehicles**

Case 3. Paper mill

The energy consumed to overcome friction **in a paper mill** is in the range 15–25%. Globally there were 8,525 paper and paperboard machines in operation in 2012. One paper machine uses on average 140 TJ of electrical energy per year. Of this, 32% is consumed to overcome friction, 36% is used for paper production and mass transport, and 32% is other losses. The friction losses in an average paper machine are in total 44.8 TJ per year, and are distributed as 32% due to friction in water-lubricated sliding in seals, doctor blades and fabric/support contacts, 23% due to friction in elastohydrodynamic rolling contacts, 22% due to friction in elastohydrodynamic rolling-sliding contacts, 15% due to friction in oil-lubricated seals and 8% due to friction in hydrodynamically lubricated contacts (see Figure 4).

This work has produced more detailed and convincing information about friction impact on energy, CO_2 emissions and costs, especially in road transport and for one item of advanced industrial machinery. This has made it possible to produce a first estimate of the friction impact in society globally. The next step will be to continue within the new FIMECC BSA programme to carry out a fourth case study on impact of friction and wear in the mining area. This will be nicely complementary as it will address a more traditional field of industry with industrial machinery working in harsh conditions, and the aspect of wear also being considered for the first time on this level.

PROJECT NAME

P4 Friction and Energy

FRECOS

CONTACT PERSON
KENNETH HOLMBERG
VTT TECHNOLOGY RESEARCH CENTRE OF FINLAND

PARTICIPANTS (ORGANISATIONS)
VTT TECHNICAL RESEARCH CENTRE OF FINLAND
ARGONNE NATIONAL LABORATORY, ARGONNE, USA

PROJECT DURATION
2010 – 2014

PROJECT VALUE (EUR)
0.080 MILLION

20% of world energy is used to overcome friction

Friction Energy and Economic Impact

Main targets & motivation

Energy is a key resource for our society today and will be crucial for our sustainability in the future. Much of our energy needs comes from non-renewable fossil fuels. However, there are limitations in the availability of these fuels in the long run. Burning of oil and other non-renewable products produces large volumes of greenhouse gases that give rise to climate change. Energy is also a major cost issue for many industries. About 100 million terajoule is used annually worldwide to overcome friction, and that is one fifth of all energy produced. The largest quantities of energy are used by industry (29%) and in transport (27%).

The aim was to carry out the Finnish part of a global survey on how much energy is consumed today to overcome friction and to replace worn-out parts and components, and to show how much energy can be saved by developing and implementing new scientific achievements and new technical solutions to reduce and control friction and wear. The survey was carried out on a global level, in countries with different levels of industrial development and in different industrial and societal demographics.

Unique methodology for calculating the global impact of friction

Results

There was a huge interest in the results when published both in the national media and internationally. The new methodology developed to calculate the impact of friction energy, CO_2 emissions and costs, from global level over industrial sectors and machinery systems down to micro-contacts in machines, is unique, and has been a breakthrough internationally. The results were referred to by US Secretary of Energy and Nobel Prize Laureate in Physics,

Steven Chu in his Perspective article in Nature "Opportunities and challenges for a sustainable energy future" in August 2012. The total global energy consumption in 2011 was 12,275 Mtoe (million tons of oil equivalent) and of that the oil consumption was 33%. Passenger cars and light vehicles consumed 28% of the total oil production, while the whole transport sector consumed 62%. Industry consumed 9% of the oil but, in addition, considerable amounts of the coal, gas, biofuels and nuclear energy. Based on very detailed analysis of three cases – passenger cars and heavy duty vehicles representing the transport sector and paper machines the industrial sector – this study presents for the first time detailed data on how much energy is lost to overcome friction and how to control it to improve the efficiency of future mechanical systems.

Transport and industry are the two largest users of energy, and are currently consuming almost one third each of the total energy production. About 30% of the energy in transport is used to overcome friction, while in industry the corresponding amount is about 20–25%. In residential and other areas, the energy used to overcome friction is less than 10%. The overall conclusion is that about 20–25% of total world energy production is used to overcome friction.

Based on the analyses carried out, it was calculated that 100 million TJ/a is used annually to overcome friction worldwide, and this is contributing 7,000 million tonnes of CO_2 annually in global emissions.

Key publications

1. Holmberg, K., Andersson, P. & Erdemir, A. (2012), Global energy consumption due to friction in passenger cars. Tribology International, Vol. 47, pp. 221–234.
2. Holmberg, K., Siilasto, R., Laitinen, T., Andersson, P. & Jäsberg, A. (2013), Global energy consumption due to friction in paper machines. Tribology International, Vol. 62, pp. 58–77.
3. Holmberg, K., Andersson, P., Siilasto, R. & Erdemir, A. (2013), Global impact of friction on energy consumption, environment, and economy. Proc. of World Tribology Congress, 8–13 September 2013, Torino, Italy.
4. Holmberg, K., Andersson, P., Nylund, N.O., Mäkelä, K. & Erdemir, A. (2014), Global energy consumption due to friction in trucks and buses. Tribology International, in press.
5. Erdemir, A. & Holmberg, K. (2014), Energy consumption due to friction in motored vehicles and low-friction coatings to reduce it. In: Cha & Erdemir (eds), Coating Technology for Vehicle Applications, Springer Verlag, Heidelberg, Germany, To be submitted in July 2014.

Number of publications: 6
Number of Master's Theses: 1

Networks and international co-operation

The survey is a part of a tribology global survey that was planned to be carried out in several countries and has been co-ordinated by VTT in Finland and Argonne National Laboratory (ANL) in the USA. The main part of the work was carried out by VTT and ANL, while the other countries (UK, Austria, Germany, Japan, South Africa, Canada, Sweden) were included as reviewing partners.

Applications and impact

The results have been disseminated widely. A very well attended press conference was arranged at VTT Technology Research Centre of Finland in January 2012, when the first case study on friction in passenger cars was published. The results were broadcast on the news on two Finnish major TV channels, in one whole page article in Finland's largest daily newspaper Helsingin Sanomat, in 15–25 Finnish newspapers and professional technical papers, in several papers abroad (France, Belgium, UK, etc.) and on several scientific and technical professional sites on the Web.
The results are already in use by researchers, industrial experts and decision-makers when considering energy, environmental and cost issues in future research and development work, as well as when setting priorities for actions to reduce energy use for sustainable solutions on the societal, sectoral, company and technical levels.

PROJECT 5: Production Technologies for Demanding Applications

The aim of this theme was to develop new material and processing technologies based on advanced powder metallurgical (PM) processing methods and melt route.

The first part focused on the development of hot-isostatic pressing (HIP) and spark plasma sintering (SPS) techniques for complex shape products and materials combinations. The new core technology for HIP processing potentially enables markets in the valve business worth tens of millions of euros, while modelling contributes to the development of complex SPS shapes. The developed SPS processing of carbon nitride (CN) and composite targets enables the development of CN-based thin film applications.

The second part focused on thermal properties of aluminium alloys and refractory materials. Thermal conductivity of aluminium alloys was significantly improved, along with clarification of the effect of microstructure on the thermal conductivity of aluminium alloys and refractory materials. Centrifugal casted pilot components were manufactured, while new cast stainless steels were developed and tested in laboratory and industrial pilot tests.

FIMECC DEMAPP gave Carbodeon a reliable way of processing carbon nitride into dense composite targets, enabling high-quality thin-films with unique optical, chemical, and mechanical properties.

Carbodeon Oy

PROJECTS:

- New Production Technologies via Melt Route
- PM Products with New Material and Processing Solutions

New Production Technologies via Melt Route

Excellent thermal conductivity of aluminium castings

The main target was to increase the thermal conductivity of an aluminium die-cast part from 120 W/mK to 190 W/mK. The target was achieved, thermal conductivity of 207 W/mK being attained with castable primary low-silicon alloy. The result is novel, unique and highly significant.

50% improvement in thermal conductivity of cast aluminium

The thermal conductivity of die-casting alloys increased considerably as the heat treatment temperature was increased. The behaviour of the three conventional die cast alloys was similar, with heat treatment up to 520 °C producing an increase in thermal conductivity of 40–50%. There was a sharp decrease in thermal conductivity as the silicon concentration of the base aluminium alloy increased to about 3%.

Alloy composition and thermal history (heat treatment) are the most important factors determining thermal conductivity. Melt treatments, however, have no appreciable effect.

Heat removal is a key need in electronics

Demand for heat removal properties in electronic and electro-technical applications (boxes, base stations, heat sinks, etc.), is increasing. Thermal conductivity of the cast alloy must be sufficient to allow heat to dissipate at a high rate, reducing the risk of component failure and disturbances in operation. The project involved close co-operation between Alteams Oy and Aalto University School of Engineering in finding ways of improving the thermal conductivity of aluminium castings, especially aluminium die-castings. The main target was to increase the thermal conductivity of aluminium die-cast parts to 190 W/mK. Methods used included optimisation of alloy composition and heat and melt treatments, while casting was by die-casting (Alteams), and sand and permanent mould casting (Aalto University).

Keeping base stations up and running

Results with high impact

The results of the work are beneficial in making aluminium cast parts with improved thermal conductivity and high heat-dissipation capacity. The applications are numerous: electronic housings, base stations, heat sinks, inverters, etc. Die-casting is an efficient and economical manufacturing process used for the mass production of metal parts. Researchers and industry alike are very excited with the results: more efficient electrical/thermal conductivity, thinner casing walls, cheap manufacture, transport and installation of the die-cast part, good corrosion resistance and excellent surface quality.

Extended lifetime and significant energy and cost savings

These unique results will also have an impact in many other applications – an improvement in heat transfer of this magnitude guarantees not only high performance of devices, but extended life time and significant energy and cost savings. The results achieved and increased competence enabled Alteams to obtain a new business segment with heat dissipation as the key driver. Deliveries of these new applications have already begun. Testing of cast products with improved thermal conductivity are currently being conducted by two of Alteams' main telecom customers.

Figure 1. **Novel aluminiun alloys enable more reliable base stations (Photo: Nokia Solutions & Networks)**

Main contact: Kimmo Pesonen, Alteams Oy

Control of thermal conductivity by composite structure

The aluminium/SiC composite was developed for high heat conductivity applications, with the highest conductivity values around 160 W/mK. However, heat conductivity is very sensitive to homogenous distribution of SiC particles.

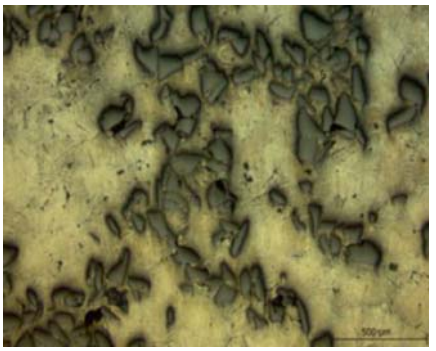


Figure 2. **Aluminium/SiC composite for high heat conductivity applications**

The thermal conductivity of masonry materials can be controlled by varying the amount of high heat conductivity SiC particles. Processing parameters should be controlled carefully, however, since porosity in the binder phase easily decreases conductivity. Masonry heat conductivity is dependent on calcination temperature, and increases significantly when the calcination temperature reaches 1,000 °C.

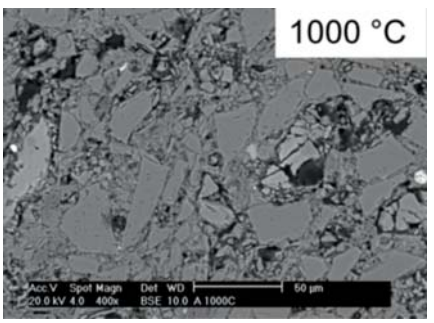


Figure 3. **Masonry with SiC particulate addition for control of heat conductivity**

Main contact: Erkki Levänen, Tampere University of Technology

Reliable cyclic oxidation testing of stainless steel

The role of high-temperature corrosion is often important in materials selection for industrial equipment, ranging from gas turbines to heat-treating retorts. Corrosion resistance at high temperatures, often combined with adequate hardness and toughness, is the most important selection parameter for steels in many end-use conditions. Because steels behave differently in temperature cycling compared to isothermal exposure to high temperatures, test equipment was developed for flexible heating and cooling rates in various atmospheres. The rig can be used at different temperatures, ranging from 200 to 1,100 °C, and in controlled atmospheres, typically with $N_2 + O_2$ mixtures as the matrix gas.

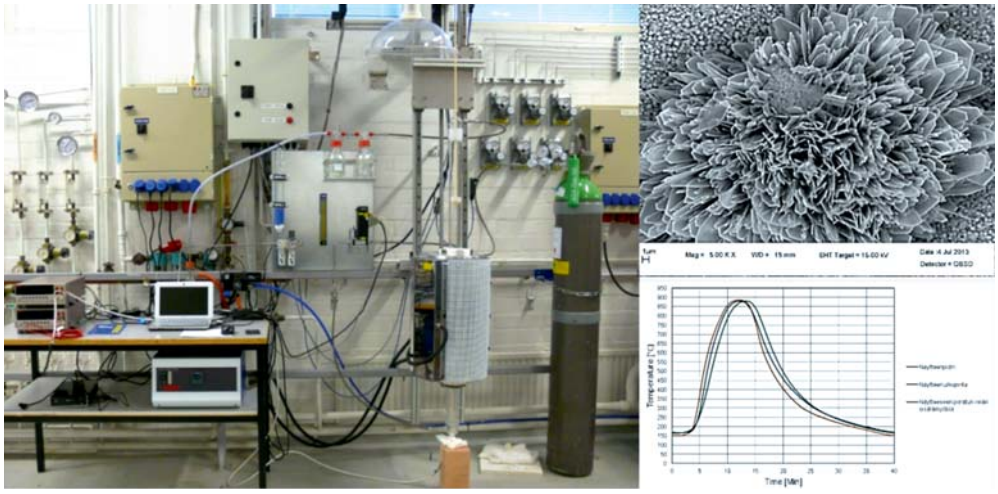


Figure 4. **Cyclic high-temperature corrosion apparatus developed for oxidation studies of cast heat-resistant steels (left and lower right) and surface oxidation morphology of an austenitic superheater tube steel (upper right)**

Main contact: Pekka Taskinen, Aalto University

PROJECT NAME

P5 Production Technologies for Demanding Applications

MELT

CONTACT PERSONS

MARKE KALLIO
METSO MINERALS OY

MIKKO UUSITALO
VALMET POWER OY

PEKKA TASKINEN
AALTO UNIVERSITY

ERKKI LEVÄNEN
TAMPERE UNIVERSITY OF TECHNOLOGY

PARTICIPANTS (ORGANISATIONS)

AALTO UNIVERSITY SCHOOL OF CHEMICAL TECHNOLOGY, AALTO UNIVERSITY SCHOOL OF ENGINEERING, TAMPERE UNIVERSITY OF TECHNOLOGY, ALTEAMS OY, KESKIPAKOVALU OY, METSO MINERALS OY, VALMET POWER OY

PROJECT DURATION

2010 – 2014

PROJECT VALUE (EUR)

2.060 MILLION

Harness of heat with materials

New Production Technologies via Melt Route

Main targets & motivation

- The DEMAPP Melt project started with the need to develop and find corrosion- and heat-resistant castings for applications in Metso Minerals' end uses in which the steels endure quick thermal cycling and high temperatures. The effect of alloying modifications on mechanical properties of new alloys was also in need of study. Project objectives were later shifted to finding economical stainless steel grades with oxidation resistance sufficient for Metso Power's fluidised boiler superheaters.
- Higher thermal conductivity of cast aluminium alloys (from the present 120–140 W/mK to 200 W/mK): demand for heat removal properties in electronic and electro-technical applications is increasing, with more waste heat to be removed from the apparatus.
- The thermal conductivity of boiler masonry is based on estimation and old modelling tables. In modern boilers, conductivity should be known precisely in order to form the basis of heat flow design. Masonry heat conductivity is currently controlled mainly by adding silicon carbide to the mass. The resulting conductivity is estimated on the basis of mixing ratios. Thermal conductivity, however, is very much affected by binder phase calcination reactions and porosity, and by the temperature itself, since the thermal conductivity mechanism changes with temperature. The objective was to measure true thermal conductivities of refractory materials and to understand the phenomenon determining the measured values.

Results

Steels

- An apparatus for testing cyclic high-temperature oxidation was built and tested in a long experimental series in various N_2-O_2-H_2O-SO_2 environments.
- Information was attained about the oxidation resistance of heat-resistant steel castings.
- Improvements in the field of oxidation resistance were achieved using thermodynamic alloy design techniques to adjust the alloying of the standard HH heat-resistant steel.
- Small steel grain size was shown to have a beneficial effect on the initial stage of oxidation.
- The sigma-phase formation was studied in cast heat-resistant austenitic and duplex stainless steels during high temperature exposure. The sigma-phase formation and the consequent embrittlement brings along a need to treat the components made of these steels very carefully at low temperatures during, e.g., the maintenance or renovation periods.

Aluminium alloys

- Heat treatment of aluminium alloys increased the thermal conductivity of the alloys studied by up to 50%. As heat treatment temperature increased, thermal conductivity of the alloy also increased.
- **Heat treatment increased the thermal conductivity of the high-pressure die-cast product by up to 15–20%.**
- Optical and SEM work shows precipitates forming within aluminium grains in the heat treatments studied. Precipitation of silicon was observed in AlSi10Mg and AlSi12, and of copper in AlSi9Cu3.
- Modification resulted in a slight improvement in thermal conductivity of the alloys studied, while grain refinement and rheocasting had no effect.
- Thermal conductivity values calculated using Matthiessen's rule and the Wiedemann-Franz law agree fairly well with the measured values in most of the alloys studied
- Alloy composition and thermal history (heat treatment) are the most important factors determining thermal conductivity, while melt treatments have no appreciable effect.
- Thermal conductivity of high-pressure die-casting aluminium alloys were studied by adding SiC reinforcement particulates into the matrix alloy. The results verified and strengthened the potential of particulate- reinforced aluminum matrix composites in improving the thermal conductivity of aluminum alloys.

Masonry

- The masonry material heat conductivity value is generally following the SiC content. However the type of binder phase and especially the porosity of binder have effect to heat conductivity value. When SiC content is increased the binder porosity increases due to more difficult packing of particles. This hinders the thermal conductivity increase.
- The thermal conductivity of masonry varies slightly with calcination temperature due to increase of porosity. When calcination is done at high temperatures, around 1,000 °C, the sintering of structure occurs and the room temperature heat conductivity increases since the phonon conductivity increases.
- The actual conductivity values are generally in the range of specifications, but processing has strong effect on conductivity, since it affects porosity. At field the masonry has thermal gradient and therefore also the conductivity gradient so the evaluation of heat conductivity over whole structure is challenging. The contact to other structures such as wall tubes and heat transfer at furnace side interface has also strong effect on heat conductivity.

Key publications

1. Ottelin, M. (2011), Heat resistant cast stainless steels in cyclic thermal conditions, MSc thesis, Aalto University School of Chemical Technology.
2. Sahivirta, H. (2012), Effect of water vapor and sulphur dioxide in cyclic high temperature corrosion of stainless steel, MSc thesis, Aalto University School of Chemical Technology.
3. Cingi, C., Rauta, V., Suikkanen, E. & Orkas, J. (2012), Effect of heat treatment on thermal conductivity of aluminium die-casting alloys, Advanced Mater. Research, pp. 538–541, Proc. 2nd International Conference on Advanced Engineering Materials and Technology, AEMT Zhuhai, China, pp. 2047–2052.
4. Rauta, V., Cingi, C. & Orkas, J. Effect of heat treatment and metallurgical treatments on thermal conductivity of aluminium alloys. Materials Science and Technology (Manuscript Draft).
5. Viherkoski, M., Huttunen-Saarivirta, E., Isotahdon, E., Uusitalo, M., Tiainen, T. & V-T. Kuokkala, (2014), The effect of ageing on heat-resistant cast stainless steels, Materials Science and Engineering: A, Vol. 589, pp. 189–198.

Number of publications: 10
Number of Doctoral Theses: 1 in progress
Number of Master's Theses: 4
Number of patent applications/patents: 1

Networks and international co-operation

One visit to Sweden: Jönköping University.

Applications & impact

Steels

- The results obtained will be used in the design and selection of cast high-temperature steels for the end use and application.
- Metso is currently performing long-term field tests with new alloy compositions. The decision to take alloys to commercial applications will be made after the tests are completed.
- The properties of cast stainless steels in cyclic-temperature applications with reference to their microstructure and assay have been analysed in detail, and the results obtained highlight the alloy development and its possible strands for various end uses. Study of mechanical properties gives valuable information for the material selection process.

Aluminium alloys

- The results of the work can be used when making aluminium cast parts with improved thermal conductivity in electronic and electro-technical applications (boxes, housings, base stations, heat sinks, inverters, etc.). Commercialisation of results is under way and the significance of the results achieved excellent.
- The possibilities for improving the thermal conductivity of high-pressure die-casting aluminium alloys were studied by adding SiC reinforcement particulates to the matrix alloy. The work has verified and strengthened the potential of particulate-reinforced aluminium matrix composites in improving the thermal conductivity of aluminium alloys.

Centrifugal casting

- Metso Minerals Oy and Keskipakovalu together developed the centrifugal casting process for steel castings. Several full-scale pilot castings were made. It was noted that centrifugal casting yielded a more dense structure in the castings while, due to faster cooling, the steel microstructure was also finer than in normal sand castings.

Masonry

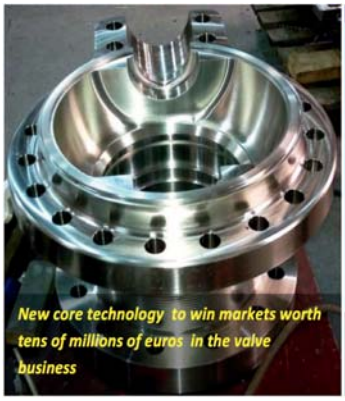
- Power boiler masonry can be designed more precisely in terms of heat flux. This leads to better control of heat distribution in the boiler, and to more economical design. Regarding mixing ratio in the phase concerned with achieving better conductivity, the key parameter in masonry design is careful processing, because of its strong effect on porosity.

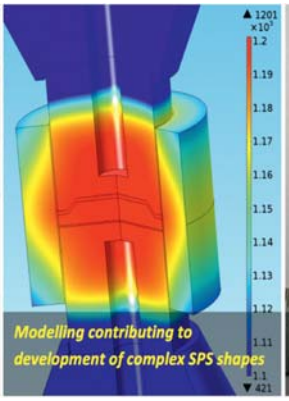
PROJECT NAME

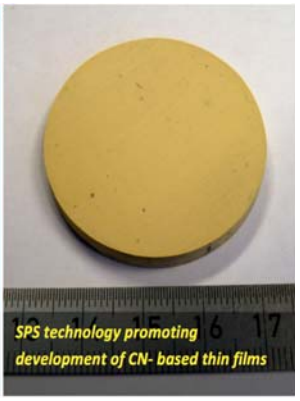
P5 Production Technologies for Demanding Applications

POCO

PM Products with New Material and Processing Solutions







Targets and related research

1. To identify, design, and develop processing of novel materials for demanding applications.
   - SPS processing of carbon-nitride-based (CN-based) composites into coating targets was optimised. This will benefit development work aimed at good quality CN-based thin films.
   - Metal-based powders containing solid lubricants (SL) were developed for HIP consolidation.
   - Zirconia powders were researched and developed for water-degradable cores.
2. To develop and optimise design and manufacturing procedures for complex SPS shapes.
   - Several complex SPS shapes were designed and compacted. The expertise gained will benefit future work aimed at SPS shapes of increasing complexity.
   - A finite element model for simulation of the SPS process was constructed. The model will enhance process control and facilitate design of complex SPS shapes.

3. Develop and optimize manufacturing procedures of HIP core and bimetal solutions.
   - HIP core technology was developed to achieve more near-net-shape (NNS) components. This technology is especially applicable in the manufacturing of complex bimetal parts. Besides the NNS, important guidelines included cost-effectiveness and ease of removal from the consolidated metal part. Zirconia based water degradable cores were manufactured also by slurry casting.
   - Solid lubricant alloys and parts were developed and manufactured with high energy milling of powders and HIP consolidation. These alloys enable low friction forces in mechanical constructions under unlubricated service conditions.

Manufacturing of bi-metallic parts with complex shape

SPS processing of CN -based materials into coating targets (Aalto University, Carbodeon)

The CN (graphitic C_3N_4) powder produced by Carbodeon consists of triazine (C_3N_3) rings linked via nitrogen bridges, forming a 2D polymeric structure with chemical formula $C_3N_{4+x}H_y$. It is a chemically inert, bio-compatible and non-toxic material, characterised by unique optical properties. CN and CN-based targets can be made into thin films (by laser-assisted cold ablation) with high wear resistance, tunable friction coefficient and exceptional optical properties.

Aalto University and Carbodeon carried out an optimisation programme for SPS processing of CN and various CN-based materials (e.g. CN–Teflon, CN–BN). After initial setbacks, a wide range of CN-based materials could be processed successfully into coating targets (Figure 1).

High-quality CN-based targets developed – key enabler for high-performance thin films

Figure 1. **The CN powder (left) and a coating target (right) made out of the powder by SPS**

A finite element model for simulation of the SPS process (Aalto University)

A finite element model for simulating the SPS process (temperature gradients, distribution of electric current) was developed to enhance process control and facilitate design of complex SPS geometries. The model is readily applicable to different mould geometries, sintering cycles, and materials. It also includes an option to implement results from master sintering curve studies to simulate densification as a function of both sintering time and temperature (Figure 2).

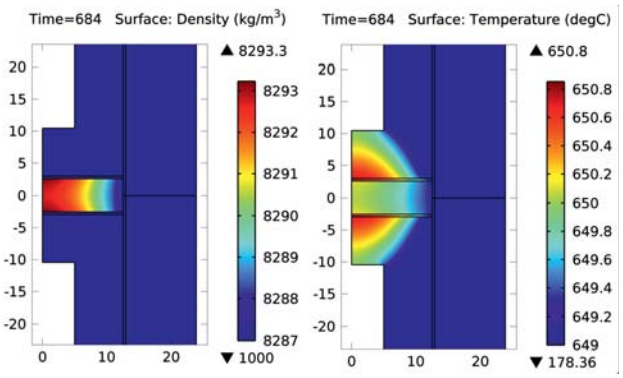


Figure 2. **Simulation results illustrating radial temperature and density gradients across a copper compact**

Slurry cast molochite cores for HIP of bimetallic valve bodies (Metso, VTT)

The use of slurry cast molochite cores was demonstrated in industrial-scale bimetal parts: a core of 220 litres for a massive valve body was successfully slurry cast; a smaller valve body with clad internal surfaces was HIPped using an axial core (Figure 3); and a valve body with clad internal surfaces was HIPped using intersecting core parts (Figure 4). The bimetal valve bodies were tested ultrasonically on-site and proven to be sound and with the desired cladding thickness.

Figure 3. The slurry cast molochite core and the bimetal valve body half as machined. The orifice surface is clad with Inconel 625

Figure 4. Slurry cast molochite core parts and the valve body block after HIP and pre-machining. The internal surfaces were clad with RALLOY® DMMC

Solid lubricant (Wärtsilä, VTT)

Metal-based NiCr powders containing solid lubricant additives Cr_2O_3, Ag, BaF_2, and CaF_2 were processed in a planetary mill. The milled powders were HIPped at 950 °C and 1,150 °C. The properly milled and consolidated parts were homogeneous and dense, containing homogeneously dispersed NiCr particles in a solid lubricant-rich matrix (Figure 5).

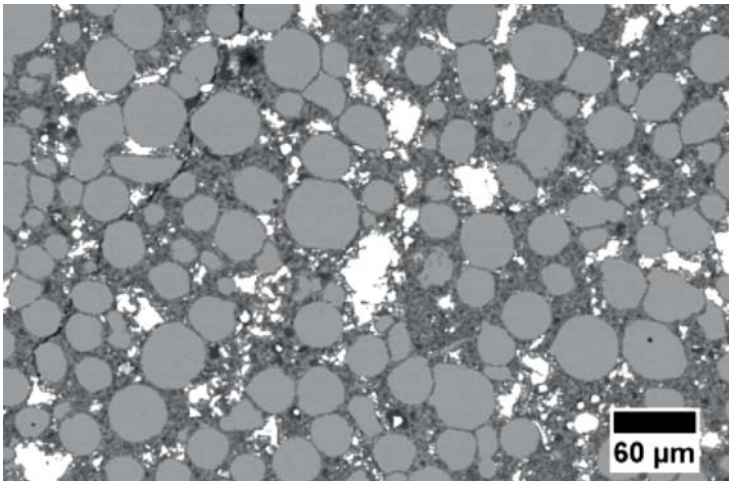


Figure 5. **An SEM micrograph showing round NiCr particles in a solid lubricant matrix**

PROJECT NAME

P5 Production Technologies for Demanding Applications

POCO

CONTACT PERSON	PARTICIPANTS (ORGANISATIONS)	PROJECT DURATION	PROJECT VALUE (EUR)
PEKKA SIITONEN METSO MINERALS OY **JUHO LOTTA** AALTO UNIVERSITY	**AALTO UNIVERSITY, VTT TECHNICAL RESEARCH CENTRE OF FINLAND, METSO MINERALS OY, CARBODEON LTD OY, WÄRTSILÄ FINLAND OY**	**2010 – 2014**	**1.755 MILLION**

PM Products with New Material and Processing Solutions

Main targets & motivation

1. To identify, design, and develop the processing of novel materials for demanding applications.
   - The manufacturing technologies (spark plasma sintering, hot isostatic pressing) used in this project enable successful processing of many otherwise difficult-to-process materials that can be used in demanding applications.
2. To develop and optimise design and manufacturing procedures for complex SPS shapes.
   - The enhanced capability of sintering complex SPS shapes has the potential to increase the industrial significance of SPS technology.
3. To develop and optimise manufacturing procedures of HIP core and bimetal solutions.
   - The improved capability of manufacturing near-net-shape bimetal components by HIPping facilitates production of components otherwise difficult and/or expensive to manufacture.

Results

- A finite element model for simulation of SPS process was constructed. The model enables better process control and facilitates design of complex SPS shapes.
- An optimised procedure was developed for manufacturing coating targets from carbon-nitride-based (CN-based) materials by SPS. The capability of manufacturing good-quality coating targets is a prerequisite for producing good-quality CN-based thin films.

- Ceramic cores for HIP can be slurry cast from molochite. The developed cores are suitable for HIP of industrial bimetal components. Molochite sand is an inert and relatively inexpensive refractory material. Slurry casting as the forming technology provides versatile geometries in tight tolerances. Cores left open in the capsule can be removed easily from the HIPped part.
- Bimetal components of Inconel 625/AISI 316L, Inconel 625/duplex, RALLOY® DMMC/AISI 316L and RALLOY® DMMC/duplex can be manufactured by HIP of powders. The soundness and thickness of the metal layers can be detected and measured using ultrasonic NDT.
- Solid lubricant alloys can be manufactured using high-energy milling of solid lubricant and steel powder mixtures. The milled powders can be consolidated using HIP.

Key publications

1. Kanerva, U., Lintunen P., Virta, J., Lotta, J., Cura, M. E. & Hannula, S-P. (2013), Effect of ZrO2 particle properties on processing and properties of the end-product. Poster presentation. POWTECH 2013, Nuremberg, Germany, 23–25.4.2013.
2. Ruskola, M. (2014), Numerical Modelling of SPS Process. Master's Thesis. Aalto University School of Chemical Technology.

Number of publications: 1
Number of Master's Theses: 1

Applications & impact

The SPS procedure developed for making carbon-nitride-based (CN-based) PVD targets is used in developing and manufacturing thin films (joint work by Picodeon Ltd Oy and Carbodeon Ltd Oy) with unique properties. The capability of manufacturing CN-based targets facilitates the manufacture of thin films with high optical, chemical, and mechanical properties.

The method developed for producing internally clad near net shape components by hot isostatic pressing has significant technical and economic implications. In the case of corrosion-resistant Inconel 625 claddings, the manufacturing cost of clad stainless steel components is remarkably lower than for HIPped solid Inconel components, and can be produced at a price competitive with commercially available weld clad components. The reliability and corrosion-resistance of HIP claddings is superior to weld cladding. Wear-resistant MMC-lined components have not previously been available. The pilot valve produced in the project is undergoing field tests at an oil refinery. In addition to valve components, the valve will be used in other process industry applications, i.e. pumps and pipe fittings. Annual turnover in the near future is expected to be several million euros.

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