DIMECC

FINAL REPORT 5/2017

DIMECC PUBLICATIONS
SERIES NO.18

HYBRIDS – HYBRID MATERIALS

2014 –
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Publisher DIMECC Oy
Korkeakoulunkatu 7
33720 Tampere
Finland
www.dimecc.com

ISBN 978-952-238-195-8
ISBN 978-952-238-196-5 (pdf)

DIMECC Publication series

ISSN 2342-2696 (online)

Graphic design and layout: Public Design Oy

English language editor: Semantix Oy

Printed in Finland: Grano Oy, Tampere, 2017

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Greater Than the Sum of the Parts

Many industrial applications in various fields require material property combinations that cannot be achieved using conventional materials. Hybrid materials consist of at least two components acting in concert to make a correlated material that intensifies the advantages of the original constituents, compensates for the disadvantages, and even shows new exceptional properties. What is sought is an outcome that is greater than the sum of the parts.

The DIMECC HYBRIDS program was designed to create new capabilities enabling the combination and use of common engineering materials in an innovative way. The mission of the program was to build a unique technology platform and world-class competencies, such as engineering processes for material selection and product design, design-related material property data for hybrid materials, and computational tools for hybrid material multiscale modeling and simulation. This hybrid material excellence created in the DIMECC HYDRIDS program provides key industrial advantages and key enabling technologies to apply advanced materials effectively in future applications.

The same principle also applies to innovation. In today's society, innovation and disruption cannot be achieved by one organization on its own. Instead, co-creation is needed, enabling systemic change and the integration of capabilities of multiple actors. Effective co-creation requires management excellence. DIMECC has created a unique world-class innovation platform and related processes, bringing actors together, facilitating cooperation toward a common goal, and making the most of all of our work.

The best examples of excellent co-creation in one of DIMECC's thematic focus areas, materials, can be seen in this final publication. I warmly thank the HYBRIDS consortium for their great collaboration. In particular, I would like to acknowledge the program management team, Markku Heino and Vilja Vara, for their effort in leading the program and mastering the collaboration among the participants. I also thank Tekes for the public funding needed in such a huge effort.

We in DIMECC believe collaboration is the key to the success and competitiveness of Finnish industry. Through the DIMECC co-creation platform, our aim is to facilitate co-creation between multiple actors, resulting in cooperation that is greater than the sum of the parts!

Essi Huttu
Vice President,
Co-creation
DIMECC Ltd

Application-driven Digitalized Development of Knowledge-intensive Materials Solutions

The DIMECC Hybrid Materials (HYBRIDS) program set the ambitious aim of renewing and strengthening the Finnish manufacturing industry by creating and effectively running a unique multidisciplinary knowledge platform for advanced materials solutions. The program has focused on solving fundamental challenges in the development and industrial application of multi-materials, such as specific composites, coatings, and layered structures, to create unique property combinations that conventional materials do not possess. The goal has been to create both novel multi-disciplinary competencies and value-added, hard-to-copy hybrid material solutions that meet tough customer and application requirements, bringing a crucial competitive edge for Finnish companies in the global market.

The identified critical materials challenges have been solved through intensive joint R&D work in four industry-led project entities, focusing on new coating materials and technologies, multifunctional composite and hybrid structures, and novel tribological solutions for selected industrial applications. As a result, a variety of important solutions have been developed, such as new wear- and corrosion-resistant, non-sticking, energy-absorbing/reflecting coatings, functional lightweight composites, hybrid structures for sensing and monitoring, or novel slide bearings and tribological contacts improving significantly the energy efficiency and operational reliability of machines and equipment. The key issue in all these has been well-defined research problems based on real application needs, and ambitious tackling of the complex phenomena through sharp multi-disciplinary experimental research and modeling.

The cross-cutting fifth project (FUNMODE; Fundamentals and modeling) has been the key tool to build the required comprehensive understanding of critical fundamental phenomena, and to develop the modeling and simulation expertise in material properties, based on real-life industrial challenges. In this, we have built comprehensive world-class capabilities in so-called Integrated Computational Materials Engineering (ICME), boosting the implementation of modern, experimental and multiscale modeling tools to solve real industrial problems effectively. The digitalized materials development enables shortening development time significantly, in many cases to a half. Providing solid understanding of complex phenomena, it also enables better reliability, predictability, and safety for components in demanding operational conditions. Our companies will get a significant competitive edge as early adopters of these novel tools.

This project also formed the DIMECC Breakthrough Materials Doctoral School (a joint venture with the BSA program, including a total of 38 doctoral projects linked to each other), which is the biggest industry-led doctoral school in Finland. But it is much more than that. It operates in a unique working mode in which the doctoral researchers, working daily in the industry-led projects of the HYBRIDS and BSA programs, team up regularly with their peers through the doctoral school events and thematic working groups, sharing thoughts intensively, coaching each other, and being coached by senior research scientists, key industry experts, and top international scientists. As a large multi-disciplinary research entity, this group solves critical research challenges, defined together with the industry, which creates important, unique know-how and competence in modern application-driven digital materials engineering. This is a significant asset for this industry ecosystem and more widely for Finnish society.

The HYBRIDS program has systematically built new and broad multidisciplinary knowledge networks. It has brought together a unique group of high-tech companies, both key corporations driving the Finnish export industry and skilled growth-seeking SMEs, covering, for example, the production and processing of various materials (nanomaterials, composites, metals, plastics), design, manufacturing, mechanical engineering, coating technologies, measuring, instrumentation, and a large number of important end products and application owners. This highly cross-technological industry group of 38 companies represents many different existing value chains and a great potential to create new ones. The best research groups in selected expertise areas, and their high-level international partners, have ensured the program's scientific significance and ambition.

Our active program management has boosted hands-on R&D co-operation and active communications within this highly multi-disciplinary ecosystem. We have arranged a variety of dedicated events to ensure fast information-sharing, and co-creation and transfer of results within the consortium, including Doctoral School workshops, project-level Impact Days, and large annual seminars gathering partners from both HYBRIDS and BSA. Dissemination of research results and other relevant communication within the program, specifically through Results Challenge News, Results Highlights, quarterly newsletters, and an internal portal, as well as the wide and systematic public communications achieved by about 50 news articles in professional journals, has contributed to a wider understanding of opportunities and exploitation of the results.

Through our intensive joint developments, made in the DIMECC ecosystem, we can proudly say that today we have formed an effective platform for the digitalized, application-driven development of knowledge-intensive multi-materials, serving real industrial needs. This is a great asset for Finnish industry and research. How it can be fully utilized depends on future actions, pretty much defined by the innovation funding environment, but also on the capability and agility of companies to adopt new things. This momentum should now be continued with smart next actions to really implement the capabilities of HYBRIDS more widely in our industry!

I wish to thank all DIMECC HYBRIDS partners and collaborators for their great co-creation work!

Dr. **Markku Heino**
DIMECC HYBRIDS program manager
Senior Consultant, Docent
Spinverse Ltd.

Strategic Research – a Natural Connection Between Industry and Academia

You have the final report of the DIMECC HYBRIDS program in your hands. It is a collection of highlight results from a three and a half year co-creation program funded by Tekes and led by DIMECC.

Before the start-up of the DIMECC HYBRIDS program at the beginning of 2014, the project had been planned for quite a long time, since 2012. The contents and consortium for the project, around research on hybrid materials, were carefully prepared and planned, and working groups were formed. A unique and new feature of the program was the large number of doctoral projects (ten at the beginning) included as a common target of research, and as evidence of the scientific value of the research. In addition, DIMECC HYBRIDS had a sister program, DIMECC BSA (research for steel materials), with 12 doctoral projects at the beginning.

The kick-off event was organized on February 11th, 2014. From the companies' point of view, a five-year program around industrially relevant research topics gave a unique possibility to search for knowledge and capability around strategic-level research topics. Typically, such research is not possible within companies' own product development, which is required to show fast results in business. Another important viewpoint was the long-term collaboration between research institutes and companies, which would develop further strategic projects in the future, and would also give the opportunity for a PhD student and a research partner to demonstrate their capabilities to companies.

Overall, the program started well and got up to a good pace. Various project teams worked nicely together and built a network of research teams around various questions of materials science. A lot of experimental and theoretical research has been done around the target topics, and many of those have also shown industrially relevant aspects to be applied after the program, and partly already in parallel with the program. Knowledge sharing and result presentation have been open between the program parties, and one can well say there has been a large collaboration team. On the other hand, it is fair to say, not everything has been perfect. However, without any less successful parts in the program, one could suspect that the strategic research is not challenging enough or that the targets are too easy or evident. And of course, we can always improve our ways of working – there is no doubt about that either.

My company, Valmet Technologies Oy, has been a member of several sub-projects. In most of them, we have achieved valuable results from research, gaining important background information to develop further the performance of our products. These include corrosion improvements, wear and endurance improvements for several process consumables in power generation, and fiber and paper-making processes. Also, it has been useful to hear from other projects and to pick some ideas for our use. Valmet also hired one scientist from the project as its own employee.

DIMECC HYBRIDS participants can be proud of their research.

Dr. **Heikki Kettunen**
Director, R & D
Valmet Technologies Oy

Hybridization

Long-term strategic research is what research institutes are expected to do. The research topics need to be targeted in close collaboration with industry to maximize the economic benefit for society. This is exactly how the DIMECC HYBRIDS program has been built up and implemented. It gathered multiple scientific and technological players from cross-discipline sectors from universities and research institutes, together with industrial actors, and crystallized research questions with scientific challenges. This combination offered a versatile network and research infrastructure to answer the research questions and also created new, not so obvious, research questions leading to new openings.

The DIMECC HYBRIDS program networked research groups related to materials science, from very close to natural science to groups near to applied research. Since the target was the same for all, this broad-ranged, interdisciplinary collaboration constructed a very efficient, smooth-running research machine. The volume of the DIMECC HYBRIDS program was great enough to create a critical mass, and it resulted very quickly in a significant number of scientific publications, which are the lifeblood of universities. These publications are mostly joint publications with industry, which is a unique characteristic of the Finnish research ecosystem. Simultaneously, the research has created spin-off innovations and ideas, which will create a competitive edge for industry both in the short- and long-term.

For universities, the long-term strategic research is a tool to educate highly skilled doctors for the research sector, both in industry and in research institutes. The DIMECC HYBRIDS program, with the Breakthrough Steels and Applications program, had a unique joint DIMECC Breakthrough Materials Doctoral School, where all the doctoral students, with their overlapping topics, were gathered in the same network. From a university perspective, this kind of networking of doctoral students from varying backgrounds and from different universities is very welcome, offering peer support for research and enabling the organization of events with internationally high-level guest speakers. Our doctoral school has received very positive feedback from students and from abroad, as well as being an organized, unique way to implement research between universities and industry.

The one indicator of successful results is the continuation of research themes after the program. Research is continued as company-driven projects, with Tekes and Academy of Finland funding, and, it is hoped, also as EU projects. All this verifies that the topics are right and the results have been successful, with different technical readiness levels, and the need for such research is continuing.

As a representative of the Laboratory of Material Science at TUT, I can clearly state that this kind of strategic, long-term interdisciplinary research has a very high impact on university research quality and profiling, and I am quite sure that other laboratories at TUT, other universities, and other research institutes will agree.

Erkki Levänen
Professor,
Tampere University of Technology

DIMECC HYBRIDS
Program Key Characteristics

Company partners (Pcs.): 36

Research institute partners (Pcs.): 7

Volumes:

Duration:	1.1.2014 – 30.06.2017
Budget:	19 M€
Company budget:	10 M€
Research institute budget:	9 M€
People involved:	110

Results:

Number of publications:	63 (+ several submitted/in press)
Number of doctoral theses:	3 (+ 8 on-going after the program ends)
Number of other theses:	10
Patents and invention disclosures:	6
Research exchange months:	34,5

Volume of spin-off projects:	20 M€ (prepared)
Enabled business potential (estimate):	2 billion €

Tuotannon digitalisointi etenee materiaaleihin

Metso ei jää laakereilla lepäämään

Termisellä ruiskutuksella monitoiminnallisia pinnoiteratkaisuja vaativiin teollisuuden käyttökohteisiin

Muovikalvo kertoo paine profiilin

Terminen ruiskutuspinnoitus valtaa uusia alueita

Materiaaleja haastaviin kulumisolosuhteisiin

Advanced coatings by novel high-kinetic thermal spray processes

Hybridi liittää kumin ja teräksen yhteen

"Tilauskirjat täynnä uusinta mallia" - Tarttumaton pinta tehostaa suomalaistyökalua

Digitaalinen materiaalikehitys luo säästöä ja tehokkuutta teollisuuden materiaaliratkaisuihin

Tutkimus maksaa itsensä takaisin

Materiaalitekniikkaan iso tohtoriohjelma

Kivet murskaksi ilman melua

Suomen kilpailuvalttina

Uudet materiaalit ja pinnoitteet

MULTIFUNCTIONAL THIN COATINGS

P1

Jyrki Mäkelä/TUT/AF; **Erkki Levänen, Petri Vuoristo**/TUT/DMS; **Mika Valden**/TUT/SSL;
Antti Markkula, Martti Järvenpää, Pasi Väisänen/SSAB Europe; **Riitta Mahlberg**/VTT;
Eero Haimi, Jari Koskinen/Aalto/MSE; **Juha Pimiä**/Fiskars Finland Oy; **Janne Siivo**/Oras Ltd;
Kari Lehtonen/LM-Instruments; **Jari Liimatainen**/Picodeon Ltd. Oy; **Marko Pudas**/Picosun Oy

Combining performance with appearance in thin coatings

Future technical applications in industrial sectors such as construction, mechanical engineering, consumer products, and special applications require novel innovative surfaces with highly diverse functions, such as an attractive visual appearance combined with special surface functions, high durability, long-term corrosion resistance, visual stability, and specific friction characteristics. Cost-effective, energy-efficient, sustainable, and innovative surface engineering solutions based on novel multilayer designs, multifunctional properties, and emerging manufacturing technologies are seen as long-term potential providers of such needs. Applications of novel multifunctional thin coatings are required both in applications with large surface areas and in products surface-treated in batch-type processes.

In metallic hybrids, one goal is to design and **create colored/dyed zinc coatings, provided by single-step processing of surfaces with multifunctional novel materials, and with novel thermal spraying**-based modification technologies. Although dyeing of metallic materials has already been done before our era, such as in patinated copper, for zinc, and also for many other metals, functional dyeing methods have not been found (except for painting) that would be applicable in construction engineering. The other goal is to investigate **novel sol-gel-based passivation coatings, thin organic coatings, and green pre-treatment techniques for hot dip galvanized steel**, which enhance surface corrosion resistance, appearance, and adhesion to final painted coatings. Novel, durable passivation products are needed to achieve end-products that are fully compatible with EU chemical legislation that will enter into force in the near future.

In polymer hybrids, the focus is to investigate industrial applications for construction (steel sheets, components, off-shore cabins, modular bathrooms, etc.) to follow the mega-trends of sustainable and energy-efficient building and special customer needs, such as clean, hygienic, antibacterial, and deicing surfaces combined with proper formability, long-term durability, and sustainability. The aforementioned concepts are quite well known at present, but the main priority for this project is to bring additional value by reaching significantly improved function compared to traditional technologies. One key to reaching more efficient function is to bring in novel application technologies, such as multilayer coating with emerging manufacturing techniques, sol-gel, siloxane, ALD (atomic layer deposition), PLD (pulsed laser deposition), PVD (physical vapor deposition), and LFS (liquid flame spraying) technologies. Furthermore, the purpose is to develop methods for analyzing and characterizing function in such surface-active thin layers.

The multifunctional coatings for components treated in batch-type processes should possess key functions such as wear-resistant, non-scratch surfaces with controlled friction, non-stick, omniphobic, and hygienic properties. The appearance of the surface is also very important, and metal-like, transparent, or colored surfaces are needed. The function of the surface should be long-term durability against wear, corrosion, and fouling. Typical applications can include household tools, dental equipment, gardening tools, glass, and other consumer products.

Key results and impacts

The multifunctional thin coating project produced significant results from support surface chemistry, through organic thin coatings and multi-layered structures, to final properties and testing methods, by utilizing a cross-discipline approach to innovative chemistry and emerging technologies. The key results and impacts are presented, from the substrate surface to the outer surface and testing, and from large-area applications to small-size batch coatings.

Multifunctional hybrid coatings for large-area applications

Decorative colored zinc coatings for enhanced visual appearance – alternative approach to painting

Several new hybrid coating methods and concepts has been demonstrated successfully in the manufacture of colored zinc coating. Development has been carried out in several steps, aiming in each step to increase the productivity of the method (Figure 1). The most successful methods to introduce color to zinc have been: a) polymer and zinc co-deposition, and b) the zinc metal special wire arc spray method.

The most successful concept has been the zinc metal special wire arc spray method. In this concept, a novel production method for zinc

Desired colors and high durability without painting.

wire with metal wire filler has been developed, which enables the deposition of the coating by a wire arc process. The filler metal was a color metal, such as copper or brass, and was planned to produce a coating that has colorful metallic particles in the zinc coating. By using this concept, an advantage is expected in manufacturing reliability, coating quality, and efficiency of coating deposition. The results at this stage will be utilized by the zinc wire manufacturer Vertic Zinc Wire, and the commercialization potential will be evaluated by steel sheet manufacturer SSAB Europe.

Company impact

"Durable dyeing of zinc surfaces does not only give the desired color that the market requires, but it also gives an opportunity to improve mechanical and corrosion protection of metal-coated steel products."

***Martti Järvenpää,** product development manager, SSAB Europe*

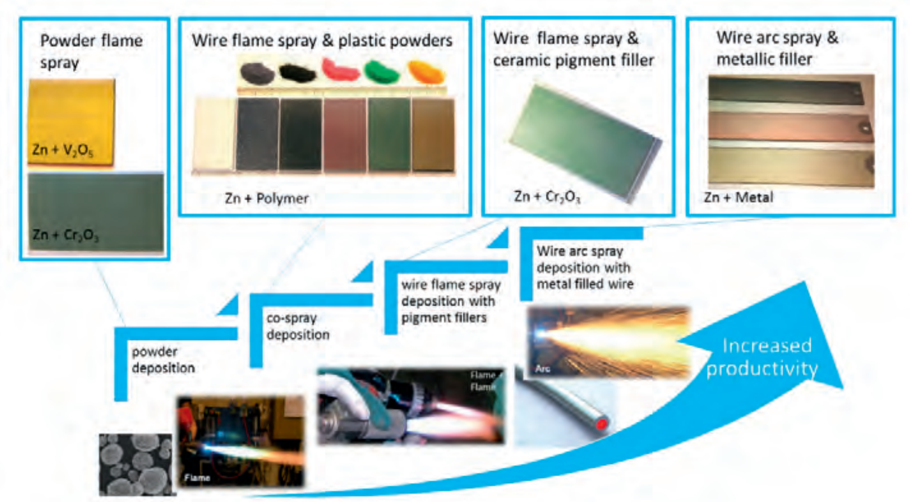


Figure 1. Illustration of the trialed concepts and resulting coatings

Zinc surface pre-treatments and passivation technologies for improved adhesion, chemical stability, and appearance

Green technology as a driver for Cr^{6+} free coatings.

The driver for pre-treatment research is the need for more environmental passivation and pre-treatment methods compared to technologies based on toxic hexavalent chromium. The scientific challenge lies in deep understanding of surface, organic, and inorganic chemistry, converging on adhesion phenomena.

One approach was to develop a waterborne **thin organic coating (TOC)** that would serve as a substrate for a multilayer color coating technology. The waterborne TOC should be applicable at the end of the galvanizing line (prior to the color coating line), directly on fresh zinc-coated steel, in order to be able to apply two further organic coating layers on the color coating line. The early stages of the project revealed that significant efforts were required to understand the interactions that govern zinc/TOC adhesion. Indeed, even after the first laboratory evaluations of complete three-layer coatings at Top Analytica, the research focus was shifted back to the optimization of zinc/TOC interactions by activation of the zinc surface and modification of the TOC formulation. Finally, parameters for strong adhesion were established and verified by industrial line trials.

Acrylic formulations were found to have the potential for waterborne candidates to passivate a hot dip galvanized (HDG) steel surface and promote paint adhesion (Figure 2). A developed TOC formulation has been successfully applied in two production line trials at SSAB Europe, followed by the application of 1–2 organic coatings on the color coating line. Good mechanical formability was obtained, and accelerated corrosion testing showed no blistering and only mild rusting, comparable to the reference coatings. The results highlight the importance of zinc/TOC interactions, and confirm that waterborne TOC layers can be employed as first layers in high-performance, cost-efficient multilayer coatings. Scientific understanding of the metal/coating interface and interactions was significantly increased. The work has set a firm foundation for tailoring of multilayer coatings for specific environments.

The zinc surface pre-treatment prior to painting was developed based on **supercritical carbon dioxide technology**. Carbon dioxide is good polar solvent, and in the supercritical stage it has the density of liquid and the mobility of gas, yet the supercritical condition is a rather mild 73 bar and 32°C. Supercritical carbon dioxide treatment allows chemical reactions resulting in conversion layer formation on the Zn surface in minutes, compared to years in normal outdoor use, before painting. This kind of conversion

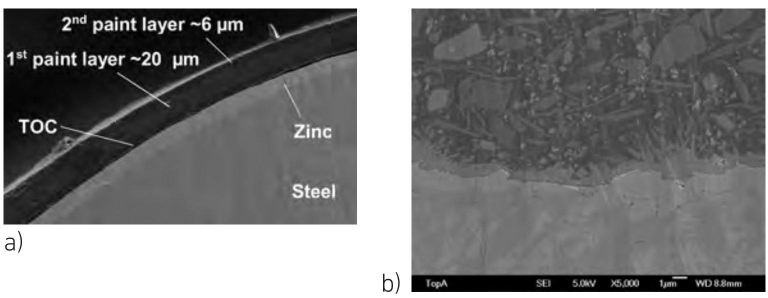
Novel conversion coatings utilizing supercritical CO_2 – the key to resource-efficient corrosion protection.

layer promotes adhesion and enables painting right after treatment. The supercritical treatment has been developed in the Ceramic Materials group at Tampere University of Technology (TUT), in close collaboration with Top Analytica for the needs of SSAB Europe.

Company impact

"During this research, we have found a significant possibility to obtain an artificial patina on HDG steel in a controlled production environment, not only to improve the corrosion protection of galvanized steel but also to minimize the undesired metal coating run-off from material and to make it post-paintable immediately after installation."

Antti Markkula, product development manager, SSAB Europe

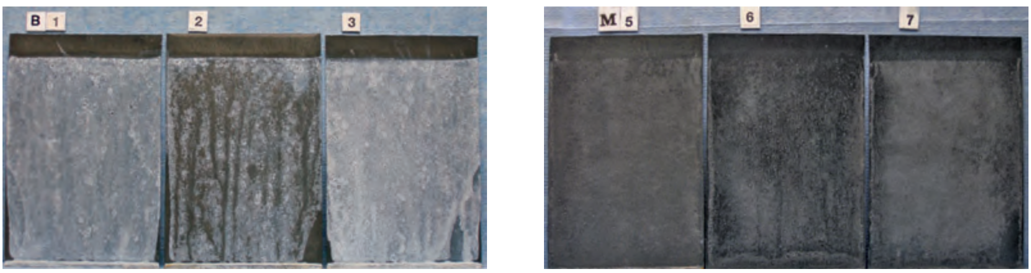


a) b)

Figure 2. **a) SEM cross-section image of an intact TOC-based three-layer coating after bending deformation, b) cross-section of a painted, $ScCO_2$-treated Zn surface showing a spiky conversion layer and good adhesion between the substrate and paint**

Surface modifications of metal substrates by novel passivation chemistry such as conversion coating treatments are considered to be practical and economical means for the improvement of corrosion resistance of metallic products. Simultaneously, the adhesion of organic coatings to the treated surface is often enhanced. A conversion coating may also provide a decorative effect on the metal surface. The effect of a black conversion layer based on trivalent Cr, together with a thin sol-gel (SG) coating, on the corrosion properties of zinc-coated steel sheets was studied. The coating development and sample preparation were carried out by VTT, and the property analyses were conducted by SSAB Europe and by Ruukki Construction.

The passivated Zn-coated specimens without a sol-gel coating tolerated poorly the weathering tests, whereas the passivated specimens with the hybrid coating performed well over 1000 hours, as shown in Figure 3. A very thin SG coating layer on a passivation layer may be sufficient to provide additional corrosion protection for zinc, since thicker coatings suffer cracking. Formability studies of the combined coating systems (black passivation + SG film) conducted by Ruukki Construction revealed severe cracking of the coatings due to bending.



a) b)

Figure 3. **a) Zinc-coated specimens (passivated, without a sol-gel coating) after 48 hours in the QCT test. The surfaces were, almost throughout, covered with white rust; b) Zinc-coated specimens (passivated and treated with a sol-gel coating) after 1000 hours in the QCT test. No white rust occurred on the specimens**

Company impact

"This work gave insight into combining two protective coating technologies in order to produce a novel hybrid coating. The results suggested that corrosion resistance and enhanced visual appearance can be sustained much longer this way than by utilizing these coatings alone, but also highlighted the need to understand better the interactions among the various coating chemicals and the substrate. This study paves the way for further implementation of totally chromium free (i.e. Si-based) hybrid passivation treatments, providing added value to metal-coated steel products."

***Risto Sipilä**, R&D manager, Ruukki Construction*

Besides the well-known self-cleaning photocatalytic glass surfaces, increasing interest in developing other **construction materials with self-cleaning properties** has been obtained world-wide. The aim was to develop photocatalytic TiO_2 sol-gel coatings for the enhancement of anti-soiling properties and the cleanability of painted steel substrates. The coating types and test matrices were planned by VTT and Ruukki Construction to have a versatile selection of coatings. Methods for measurements of the photocatalytic activity were also developed alongside the coating studies (VTT). The outdoor tests for the coatings were planned, and each year a set of coatings was placed on the test field and evaluated by HAMK University of Applied Sciences. In general, no clear differences in the anti-soiling or cleanability properties of the coatings, nor any compared with those of the substrates themselves, were obtained.

To minimize solar heating of dark gray coatings, utilization of NIR reflective pigments (perylene black) and filler materials (TiO_2) were studied. Experimental paint formulas were generated, test samples were painted, and spectral reflectance, as well as thermal emittance of the surfaces, was measured. Moreover, heating of the coatings was field-tested under solar irradiation. The experimental coatings showed enhanced thermal performance compared to a reference surface. Furthermore, the effects of both top coating and primer thicknesses on spectral reflectance were studied. The effect of substrate and primer, as well as primer thickness, on NIR reflectance was observed when perylene black pigment was used in the paint (SSAB Europe, VTT, Top Analytica, Aalto University). The heat-reflective coatings will be designed and prepared as a collaborative effort among the partners.

New testing methods for the evaluation of formability and long-term durability of functional coatings were developed by HAMK. The developed method simulates the soiling properties and cleanability of novel easy-to-clean coating surfaces in a much shorter time than in real outdoor conditions. A new kind of T-bend testing procedure proved to be good practice in revealing the effect of forming temperature on coating damage during forming, when the specimen was exposed to humidity after forming. X-die testing was used to reveal the effect of severe deep drawing on the integrity of different color coatings. X-die testing was also used to study how forming affects corrosion behavior. The soiling properties of new easy-to-clean coatings have been studied both in outdoor conditions and in a new testing set-up (Figure 4) that was designed and built in HAMK. Because the first visible biological developments begin generally after one year of natural exposure, at the earliest, and in the case of coil-coated surfaces may take several years, there is a need for accelerated tests. An accelerated algae-growth testing machine for these materials has been developed.

Figure 4. **Accelerated algae-growth testing in the laboratory. Samples are at 45 degrees, like on a roof in reality. An algal suspension circulates in an aluminum sprinkling rail that spreads water on the top of the samples, running down their entire surface**

Multifunctional hybrid coatings for batch processing and component coating

Chromium-free wet processable thin coatings for bathroom appliances and kitchenware with enhanced surface cleanliness and hygiene

Chrome plating is used as a thin coating layer for decorative purposes, such as on vehicle trims and in kitchen and bathroom appliances, to give a shiny mirror-like appearance. Due to the environmental and health issues related to the deposition processes, abrasion-resistant replacement treatments for chrome plating are in great demand. In addition, future regulations and limitations for the usage of chromic acid are setting goals for alternative treatments. In this project, wear-resistant and hygienic coatings with controlled friction for batch-type applications are to be developed using sol-gel technology (by VTT). Chrome-plated surfaces were used as the reference material when the properties of the thin coatings were determined. In laboratory tests, the scratch/abrasion resistance of polymeric bathroom appliance surfaces showed improvement with Zr- and Si-alkoxide-based hybrid coatings, or when nanoparticle additives were incorporated into Si-alkoxide-based hybrid coatings, as shown in Figure 5.

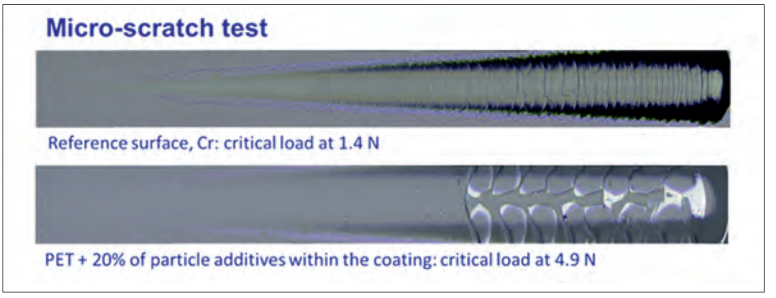


Figure 5. Chrome-plated polyester substrate (upper image) and the polyester substrate coated with a Si-alkoxide-based thin film with nanoparticles (lower image) after micro-scratch testing. The critical loads leading to surfaces damage were 1.4 N and 4.9 N, respectively

According to the industrial partner (Oras), wear resistance is dependent on the hardness, friction, elastic properties, and structure of the coatings. In this study, attention has been focused on hard and wear-resistant coating components, keeping in mind that the surface structure of the coated surfaces will meet the requirements typical for easy-to-clean surfaces (e.g. smooth, non-sticky). Valuable knowledge of the promising compositions for wear-resistant hybrid thin coatings and of deposition/curing parameters suitable for polymeric substrate profiles has been gained. This is a step toward a production-ready coating and method combination.

Fabrication of omniphobic surfaces using layered nanostructured coatings

Among the family of functional coatings, progress towards omniphobicity is presently one of the main fields of interest. This covers universal repellence against different liquid compounds, not only against water or water based 'dirt', but also against oil-based and other organic compounds. For ultimate repellence, the term superomniphobicity is used. It is generally believed that these superomniphobic features are best achieved by a controlled hierarchical surface structure containing both micro- and nanoscale structures, plus controlled chemistry of the topmost layer of the surface. In the project, our overall aim is to develop a durable nanostructured surface on a stainless steel substrate, which would repel various liquids simultaneously.

Unique thin-film coatings developed – toward universal repellence.

Aerosol physics from TUT, Surface Science Laboratory from TUT, Picosun, and Fiskars Finland developed a combination of nanoscale coatings in a layered structure to introduce self-cleaning and superomniphobic properties to a stainless steel surface. Different thin-film coating technology combinations were tested to achieve the common goal. From the obtained data, it became obvious that the highest omniphobicity was achieved by combining three different superimposed layers, and that all three of these were needed to achieve the required performance.

Company impact

"The developed technology is unique and it offers a solid platform for further development."

Juha Pimiä, *R&D manager, Fiskars Finland*

The pulsed laser deposition (PLD) method was developed for thin-film coating applications, together with Picodeon and TUT. The main focus was on the development and control of raw material target composition and manufacturing techniques. The research resulted in a large set of doped targets in which the microstructure and dopants were varied in a controlled way.

Sharp thin-film edges and non-stick multilayer coatings for hand-held instruments

The performance of high-end dental instruments was improved with two new thin-film coatings. For curettes (hand instruments used to remove hardened dental plaque), it was shown that a choice of a harder base steel material combined with corrosion protection by thin-film coatings gave superior wear performance compared to that obtained using the commercial wear-resistant coatings on stainless steel commonly used in dentistry. The thin-film coating provides the necessary corrosion protection for the daily autoclaving of the instrument, while the harder base material dramatically reduces the need for re-sharpening. This approach has enabled LM Instruments to bring a new product (Sharp Diamond, Figure 6) to the market, with wear performance superior to previously available instruments. Aalto University also developed a hybrid PVD/ALD multilayer coating, which showed an order of magnitude superior corrosion protection compared to commercial PVD coatings.

Corrosion & wear resistant, anti-sticking coatings for dental instruments.

Non-stick thin-film coatings were investigated for restorative instruments (filling of cavities in teeth), in order to reduce unwanted sticking of the restorative composite material, which would ease the operations done by dentists and reduce the risk of later filling failure. The evaluation of commercial non-stick coatings helped LM Instruments to develop a new product (Dark Diamond, Figure 6), which has received positive feedback from customers. Aalto University also developed a novel non-stick coating based on surface structuring by etching, surface stabilization by ALD, and surface chemical modification by self-assembled fluoropolymer. This coating renders steel surfaces superhydrophobic, and vastly improves the non-stick performance, as shown in Figure 7.

Company impact

"Based on feedback from dentists, Dark Diamond improves the performance of restorative instruments. By staying sharp significantly longer, the maintenance costs of Sharp Diamond instruments are remarkably lower compared to traditional instruments."

Kari Lehtonen, *development manager, LM Instruments*

Figure 6. **LM Instruments products Sharp Diamond (left) and restorative instrument Dark Diamond (right)**

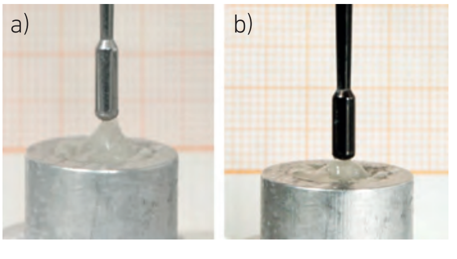


Figure 7. **a) A non-coated restorative instrument pulled out of restorative material; b) a superhydrophobic coated restorative instrument pulled out of restorative material. The follow-up distance of the restorative material can be reduced by 60% by superhydrophobic coating**

Conclusion

The project showed clearly the research benefits of strategic long-term research that combines industrial experts and academic researchers with interdisciplinary expertise. Industrial challenges can be opened to scientific research questions, and the consortium is able to find common themes and general answers, and to apply this principle to individual challenges. The thin functional coatings project is a very good example of such an approach, and it has already offered several answers, but the real strategic benefit was not totally achieved, due to shorter implementation than planned.

Further information

KEY PUBLICATIONS:

Xiaoxue Zhang, Saara Heinonen and Erkki Levänen, Applications of supercritical carbon dioxide in materials processing and synthesis, RSC Advances vol. 4, (2014), 61137.

J. Nikkola, Microcapsule-protected actives reduce leaching, Eur Coatings J 2014-4 36–40.

Leena Vuori, Harri Ali-Löytty, Kimmo Lahtonen, Markku Hannula, Elina Lehtonen, Yuran Niu, Mika Valden: Improved corrosion properties of Hot Dip Galvanized Steel by nanomolecular silane layers as hybrid interface between HDGS and top coatings, Corrosion, Vol. 73, No. 2, 2017.

Mikko Långvik, Kauko Jyrkäs, Antti Markkula, Meri Rosenberg New T-bend testing method to examine formability of color coated steel sheet in different temperatures, Proceedings of the METNET Seminar 2015 in Budapest/ Kuldeep Virdi and Lauri Tenhunen (editors). – Hämeenlinna : HAMK University of Applied Sciences, 2015. – (HAMKin e-julkaisuja, 1795-424X ; 30/2015). – 978-951-784-763-6. – s. 102–111.

J. Leppaniemi, J. Lyytinen, O. Elomaa, K. Suomalainen, J. Koskinen, The influence of PVD coatings on the wear performance of steel dental curettes, Key Eng. Mat. 674 (2016) 289–295.

CONTACT PERSONS:

Jyrki Mäkelä (TUT/AF), Erkki Levänen, Petri Vuoristo (TUT/DMS), Mika Valden (TUT/SSL), Antti Markkula, Martti Järvenpää, Pasi Väisänen (SSAB Europe), Riitta Mahlberg (VTT), Juha Pimiä (Fiskars Finland Oy), Eero Haimi, Jari Koskinen (Aalto/MSE), Kari Lehtonen (LM-Instruments), Jari Liimatainen (Picodeon Ltd. Oy), Marko Pudas (Picosun Oy), Janne Siivo (Oras Ltd)

PARTICIPANTS:

Fiskars Finland Oy, LM-Instruments Oy, Oras Ltd, Picodeon Ltd Oy, Picosun Oy, Piikkio Works Oy, Ruukki Construction Oy, SSAB Europe Oy, Aalto University, HAMK University of Applied Sciences, Tampere University of Technology, VTT Technical Research Centre of Finland

MULTIFUNCTIONAL THICK COATINGS AND COMPOSITES

P2

Jarkko Kiilakoski, Heli Koivuluoto, Jussi Laurila, Erkki Levänen, Ville Matikainen, Jussi Silvonen, Petri Vuoristo, Tommi Varis, Davide Fantozzi/TUT; **Tomi Suhonen**/VTT; **Simo-Pekka Hannula**/Aalto; **Ulla Kanerva, Olli Tuovinen, Mikko Uusitalo**/Valmet; **Sauli Seppänen**/Abloy; **Jussi Larjo**/Oseir; **Jukka Finne**/Kuopion Konepaja; **Jukka Koivunen**/Virtasen Koneistamo; **Mari Lindgren**/Outotec Oy; **Timo Rantala**/TKM TTT Finland Oy; **Kari Vierimaa, Jussi Hellman**/Metso Flow Control Oy; **Seppo Heiskanen, Ahti Ekdahl**/Kokkola LCC Oy; **Juha Rintala**/Telatek Service Oy

Advanced materials processing creates multifunctional properties and performance to thick coatings and composites

Summary of the project's motivation and achievements

The project focused on processing, structure, properties, performance, and industrial use of novel multifunctional thick coatings and composites made by technologies such as novel thermal spray coating processing, advanced weld and laser surfacing, and braze coating. The ultimate target was to create significant value and competitiveness for Finnish industrial companies by extensive research and development of coating materials and coating manufacturing processes.

Thermally sprayed metallic, metal-matrix composite (hard metals) and ceramic coatings are widely used in Finnish industry as protective coatings against different types of wear and corrosion. Known limitations for the use of these coatings are often related to weakened properties deriving from detrimental changes in phase structures in the processing step, or due to material limitations due to the present commercial technology. Material selection and tailoring, together with spray process optimization, are seen as a route for significantly better, multifunctional coatings. The improvement of coating properties and application-related performance was the main research content in this project. Operational reliability of thermally sprayed coatings and substitution of hazardous or strategic elements in the coating materials are required now and in the future. Therefore, a key driving force for this project was the increasing demands of processes for new material solutions that were not yet available. The main idea and novelty was to understand the relationships and influencing factors between the manufacturing process, microstructure, properties, and high performances, and to transfer this understanding to new materials and processing methods that would create a competitive advantage for Finnish industry in the future. **Combining novel thermal spraying technologies and new material technologies with systematic multiscale material modeling**, and understanding of the phenomena, is seen as a way to revolutionize the possibilities for coating solutions in extreme conditions. The target of this project was to increase the already high level of knowledge in Finnish research institutes and industry to become a top reference in the world.

The research focused on **novel high-kinetic spraying of metallic and hard metal powders, process optimization, and characterization of coating properties and performance.** Significant advances were obtained in this area during the project. New coatings with various multifunctional properties, such as high wear resistance, chemical stability, high-temperature corrosion resistance, low friction properties, high ductility, and cost-effectiveness, were developed. Moreover, developments of powder materials for thermal spraying, as well as diamond-braze material-joint properties, were obtained to achieve better structural and mechanical properties and performance in surface engineering solutions. Process optimization for industrial components was largely done in the industrial projects. Marked improvements in damage tolerance of thermally sprayed ceramic coatings were also achieved. An additional output was the development of testing systems for industrial requirements for the coatings and materials.

> ***New multifunctional coatings bringing resistance to wear & high-temperature corrosion, chemical stability, low friction, high ductility and cost-effectiveness.***

Key results and impacts

Metallic and hard metal coatings with high chemical and temperature resistance, low wear rate, and low friction properties

Novel wear- and corrosion-resistant coatings were achieved by utilizing a modern high-velocity air-fuel (HVAF) thermal spray process. The HVAF spray process has shown great potential in producing protective layers for demanding applications. The global competition is continuously increasing, and companies need to be able to provide customers with improved component and process performance. The new material solutions, combined with modern processes, play a key role in this challenge. The research focus was set particularly on the HVAF spray process and on understanding the processing-structure-properties-performance relationships of sprayed metallic and hard metal coatings. Such coatings are widely used in wear, corrosion, and high-temperature applications. The main achievements during the project were: 1) determination of the operation window of the spray process for commercial materials, 2) development and spraying of novel metal-matrix composite materials, and 3) evaluation of the performance of the new HVAF sprayed coatings compared to the

> ***Whole value chain involved – combining materials, processes, monitoring, applications.***

current industrial standard high-velocity oxygen-fuel (HVOF) sprayed coatings. The research was done under a collaboration platform, Thermal Spray Center Finland – TSCF (TUT and VTT), with the industrial partners involved in this project. A significant benefit was running the project under a large collaboration network involving international collaboration, powder manufacturing-coating, production characterization, and testing-modeling.

The operation window of a thermal spray process is typically defined by linking operation parameters to particle parameters, such as temperature and velocity. The measurements are carried out using online spray diagnostic systems, based on optical sensors (Figure 1). The finer particle size commonly used with the HVAF spray process, and the lower process temperature compared to HVOF spraying, together set requirements for the online diagnostic systems. SprayWatch is one such measurement system based on a CCD sensor and manufactured by Oseir Oy Ltd (a project partner). At the start of the project, the latest SprayWatch camera was limited to 1400°C particle temperature at lowest and 900 m/s particle velocity at highest, which are typical values for the HVAF spray process. The aim was to extend the operating regime of SprayWatch by attaining a faster and more sensitive sensor. A new monolithic structured optical filter was designed, and the fabrication process was automated to reduce the unit cost and to improve spatial uniformity. The CCD sensor sensitivity and exposure time were enhanced to match the requirements. In addition, sensitivity to flame background radiation was considerably reduced, which improved the accuracy of the temperature measurement. As a result of these enhancements, the performances of the new SprayWatch 2s/4s class sensors were significantly improved, and the temperature and velocity limits moved to 1100°C and 1600 m/s, respectively.

Improved wear and corrosion properties obtained by the HVAF spray process.

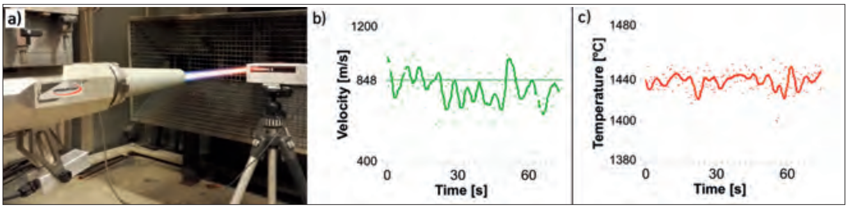


Figure 1. The enhanced SprayWatch sensor was used to measure particle properties: a) set-up for measurement, b) measured particle velocities, and c) measured particle temperatures

In addition to determining the process window, a comparison of several HVOF and HVAF processes was done during the research project, by spraying commercial WC- and Cr_3C_2-based hard metal powders. The results showed clearly that improved wear and corrosion properties can be obtained by using the HVAF spray process. As an example, the high temperature corrosion performance of the Cr_3C_2-based coatings was improved due to a denser coating structure and controlled particle temperature.

Company impact

"During the Hybrid materials project, Valmet Technologies has got valuable, new information about novel thermal spraying processes and new materials solutions. Valmet has utilized this information to develop new coating solutions for modern paper industry components."

Ulla Kanerva, *senior R&D engineer, Valmet Technologies*

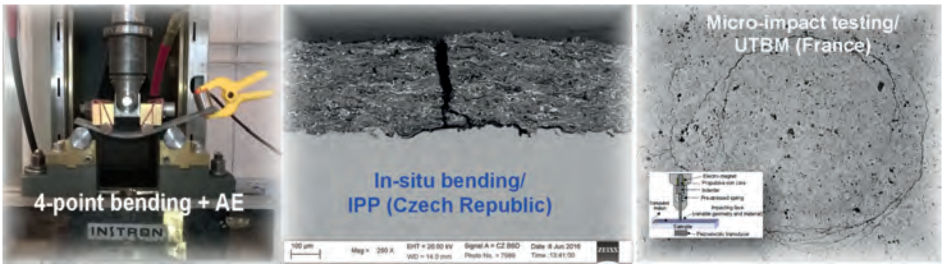
Ductile and damage-tolerant ceramic coatings by materials and coating process development

The development and utilization of new spray processing methods and materials have been the focus point in the development of damage tolerance of ceramic coatings. The research work involved powder development, including material combinations, phase and dispersion strengthening, and development of novel thermal spray coating processes, such as plasma, HVOF, and suspension spraying of ceramic materials. One of the most important topics was to develop novel characterization and testing methods in order to evaluate the ductility and damage-tolerance properties of ceramic coatings, and to introduce these to the mechanical models for ceramic coatings. Testing of ductility and damage tolerance was done using four-point bending with acoustic emission, in-situ bending, and micro-impact testing, in collaboration with international partners.

Novel ceramic powders were developed and optimized. Compositions such as Al_2O_3-ZrO_2 and Cr_2O_3-Cr were studied. In addition, new oxide-SiC-based powders, such as $MgAl_2O_4$, $MgAl_2O_4$-SiC, Al_2O_3-ZrO_2-SiC, TiO_2-SiC, and Cr_2O_3-SiC were developed and sprayed using the HVOF spray process. Commercial and experimental powders were evaluated in the laboratory and on pilot-scale components. Bending studies at macro- and micro-level, and impact, cavitation-erosion, and indentation measurements were used to analyze the

A family of novel ceramic powders developed and optimized.

coating properties related to damage tolerance (examples in Figure 2). Furthermore, the effect of spray angle on the deposition efficiency and coating quality, the spraying of multi-shaped components, and process development for shaped components using robotics were researched by industrial partners involved in the project.



a) b) c)

Figure 2. **Various measurement techniques to evaluate the strain-to-fracture and ductility properties of ceramic coatings. a) 4-point bending test with acoustic emission detection; b) in-situ bending test with SEM imaging; and c) micro-impact testing of the surface of ceramic coatings**

Company impact

"The research done on the Hybrid materials project gave valuable information on factors affecting the toughness of brittle ceramic coatings and their measurement methods. This serves as the basis for further development of more ductile ceramic composite coatings."

Jari Knuuttila*, director, Millidyne Oy*

Fracture toughness improvements in Cr_2O_3 were obtained by adding graphene-based materials to the matrix. In addition, different ceramics known to have high toughness were applied for the same purpose. Fracture toughness of Cr_2O_3 was improved almost four-fold by the addition of only 1 vol% of graphene oxide. Moreover, when Cr_2O_3 was modified by 1 vol% nano-size ZrO_2, three times better fracture toughness was achieved without compromising its hardness. The highest improvements of fracture toughness were 3.8 fold with the addition of chemically mixed graphene oxide and 3.5 fold with Al_2O_3 + 5 vol% Mo additive respectively. For the latter, when the additive amount was 1 vol% the improvement was 3.1 fold, while the hardness was even higher than pure Cr_2O_3. The results are summarized in Figure 3.

3–4 fold increase in toughness with graphene oxide and other nanoadditives

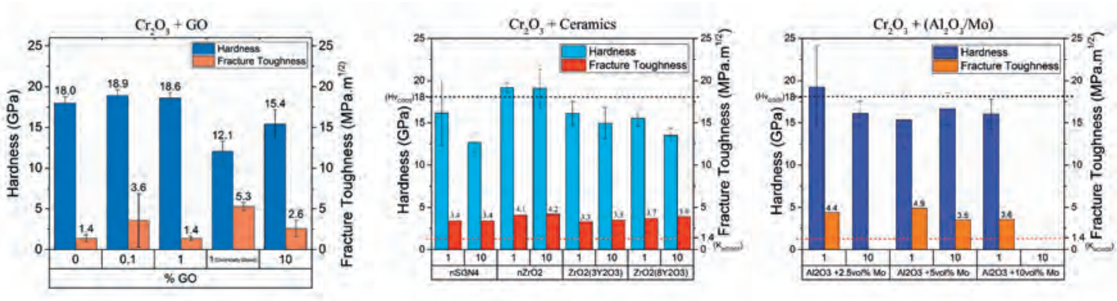


Figure 3. Change in hardness and fracture toughness of Cr_2O_3 composites relative to pure Cr_2O_3 with the addition of: a) rGO, b) nano-sized ceramics, and c) Al_2O_3 with Mo.

In this approach, the most significant result was improving the fracture toughness without compromising the hardness of the original material. Therefore, there was interest from companies especially with regard to graphene-containing materials. The challenges were homogeneous mixing of rGO in a ceramic matrix (e.g. chemical mixing made a significant difference) and keeping the additive amount low.

In the modeling research, the approach was to integrate the process-structure-property-performance linkage through modeling and simulation, as well as by experimental techniques. Modeling actions focused on material processing (a phase field code developed by VTT in collaboration with McGill University, e.g. solidification models with different cooling rates) and mechanical performance (e.g. the effect of coating structure on damage tolerance), for which an example is shown in Figure 4. New metallic, ceramic, and composite powders and coatings were manufactured, and performance was validated through experimental efforts. For example, a new type of ceramic coating with small inclusions of metallic phase was discovered through modeling, and experimental efforts aimed for a coating that has the wear and corrosion resistance of a ceramic coating but the ductility and damage tolerance of a metallic coating.

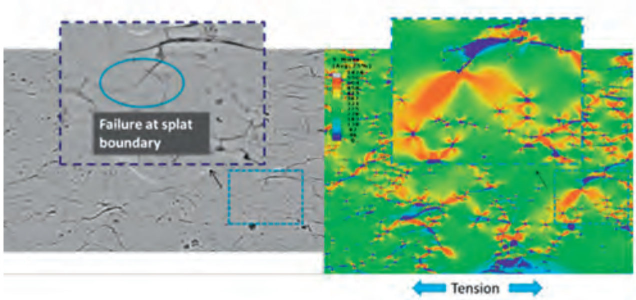


Figure 4. **Microstructural model of a thermally sprayed ceramic coating and its modeled behavior under loading**

Understanding the interfacial properties of diamond particles and braze coatings

Diamond is the hardest material and therefore it is the most wear-resistant solution for grinding grits in novel mechanical pulp-manufacturing process equipment (Figure 5). The objective of the research related to understanding the properties of brazed coatings with diamond grinding grits was to increase understanding of interactions and interfaces between abrasive particles and filler metal materials in vacuum-brazed surfaces, solidification mechanisms and resulting structures in filler metal with various combinations and ratios of filler metal components, the roles of filler metal components in melting characteristics, wetting characteristics, interactions between filler metal and abrasive particles, factors affecting corrosion resistance in respect of the above, factors affecting the ductility of joints in brazed systems, and increasing general understanding of production and characteristics of coated abrasive products in Finland. The work concentrated on **brazing of super-abrasive diamond single crystals with nickel-based, corrosion-resistant, and high-strength braze materials**. The basic motivation for the studies was to achieve a fundamental understanding of the processing mechanisms, the material structures in the layers between the braze and diamonds, the level of mechanical strength of the braze joint with diamond, and the interfacial properties of the multifunctional abrasive surfaces.

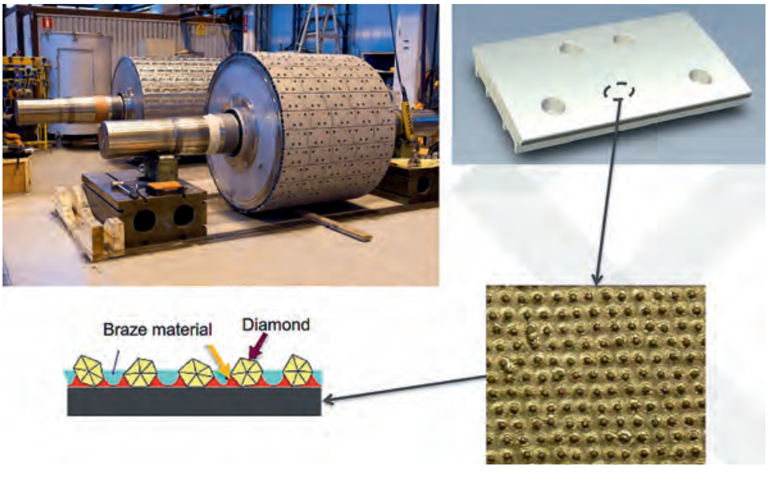


Figure 5. Multifunctional brazed coatings with diamond grinding grits in mechanical pulp-manufacturing equipment

Detailed information about the braze structures were collected and analyzed using modern research methods, from different braze material options and brazing procedures. This was done to produce new scientific information on the effects of brazing process parameters and braze material parameters on the structure of the construction. Altogether, the results led to better performance of final products and a basis for new applications with brazed diamonds with high strength and corrosion resistance. In the brazing process, the silicon and particularly chromium used as alloying elements in the brazing material react with the surface of the diamond crystal, which influences the diamond surface, wettability, and interfacial microstructure of the braze layer. Thin carbide layers on the diamond surfaces are formed, improving the wetting behavior and diamond hard particle bonding to the braze material (Figure 6). However, the surface of the diamond is also affected by the reaction, leading to carbon dissolution and the formation of a rough diamond surface after brazing, which can reduce the mechanical strength of the diamond crystals. High residual stresses are formed after cooling down the construction to the ambient temperature. These interfacial reactions are expected to define the mechanical usability of the abrasive tools manufactured by this technique to withstand the hard operation conditions in which they are used.

During the studies, **it became evident that the braze materials used at this time as high-strength and corrosion-resistant brazes are not optimum materials when super-abrasives like diamond are brazed.** These materials were developed for brazing stainless steels and other metallic materials. In particular, the high chromium content of these alloys reacts with the carbon of the diamond and the mechanical strength of diamond single crystals is lost. This is the main reason why development work on new, more suitable brazing alloys has started on the basis of the results of this project: the achieved project results give good guidelines and a basis for this further important development work.

a) b)

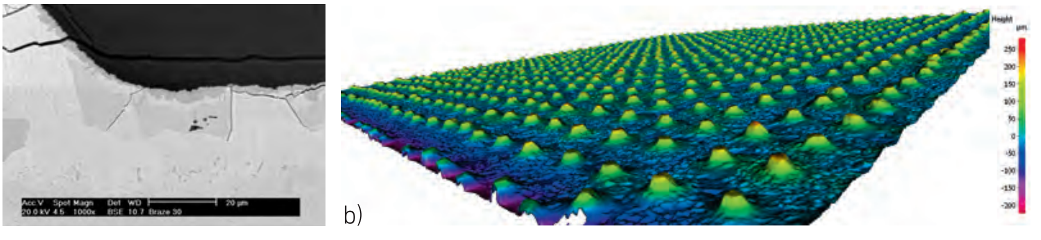


Figure 6. a) Carbide layer between the diamond single crystal and the braze material; diamond is seen as black in the upper part of the image, and b) diamond single crystals brazed with nickel-based braze material on the tool surface

It became evident that the mechanical properties of the diamond single crystals can be improved if the brazing materials are developed to be more suitable for brazing the diamond. More effective and durable grinding tools are to be developed and produced with optimized interface structures between the diamond particles and the braze coating material chemistry. In general, this kind of hybrid material tool can be used in hard material (stone, concrete, etc.) cutting, drilling, and finishing, and also in other applications where hard materials are involved. This gives us the chance to develop and produce better-lasting and more stable energy-efficient grinding surfaces for different applications.

Thermal properties of thick ceramic coatings and bulk linings for power generation boilers

Part of the fluidized bed boiler is covered with refractory materials. The importance of the thermal properties of refractories in boilers is increasing, as a large portion of the boiler is a furnace is covered with refractory materials, when dirty fuels are combusted. The results were in improving the capability for understanding the thermal properties of refractory materials and in designing optimized refractory linings for boilers. Improvements in the capability for testing thermal properties of refractories were also obtained. Incinerator furnaces are today increasingly deployed in power generation processes. In these processes, it is crucial that just the right amount of thermal energy can be taken in each process segment. This can be accomplished by the proper design of boiler linings. For this, the right information about thermal resistances in the lining cross-section is important. Thermal resistance in the boiler lining is a sum of the thermal resistances of the constituents of the lining cross-section. In refractory lining, there is a castable refractory with thickness of a few centimeters, which is anchored by studs with metal tubing. The thermal contact resistance in the castable/metal interface has so far been more or less unclear. However, it can play an important role in total heat transfer. Different thermal response measurements were accomplished to explore the thermal properties in each part of the refractory lining. In addition to the scientific effort in the project, new practical equipment for the measurement of the thermal response of refractory lining was conceived. Later, this work initiated a new bilateral project with one industrial partner.

Thermal diffusivities of pressure vessel steel, ceramics, and their stacked combinations were measured. From the measured diffusivities, thermal conductivity and thermal resistance were calculated using the following formulas:

$$k = \alpha c_p(T)\rho(T)$$

$$R = \sum \frac{l_i}{k_i} + \sum_{i}^{i+1} R_{c_{i,i+1}}$$

where (k) represents thermal conductivity (W/mK), α thermal diffusivity (m^2/s), $c_p\ (T)$ specific heat (J/kgK), $\rho(T)$ density (kg/m^3), R the sum of all thermal resistances in layered material (m^2K/W), li thickness of an material layer, and $R_{c_{i,i+1}}$ thermal contact resistance in interfaces. Thermal conductance was readily calculated, since it is the reciprocal of thermal resistance. First measuring steel, oxidized steel, and ceramic samples individually, and then as a stacked free-standing installation, made it possible to calculate only thermal contact resistance and conductance incorporated in the steel/ceramic interface.

In order to reach comparable operational conditions, steel samples were heat-treated at 450°C and 650°C to grow an oxide layer on top of the steel samples. From the calculated results, only thermal contact resistance and conductance of the interface could be extracted. Thermal contact resistances of the studied interfaces are shown in Figure 7.

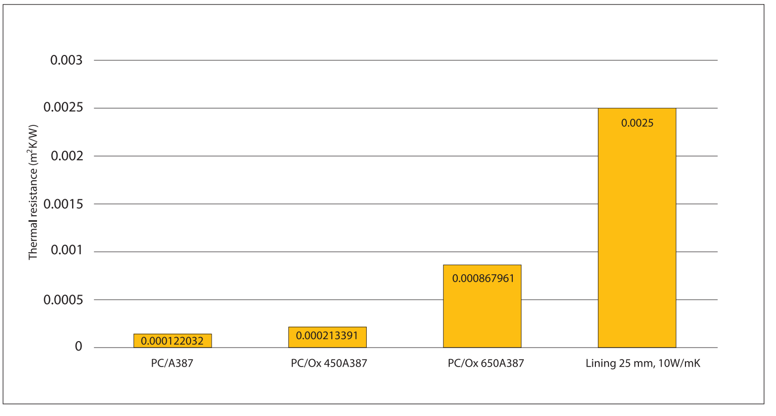


Figure 7. Thermal resistances of sample interfaces (three bars from the left) and reference refractory lining with a thickness of 25 mm and thermal conductivity 10 W/mK

The thermal resistance of paint at the metal surface was also measured, to find the increment of a thin paint coating to total thermal resistance. The importance of a 50 µm thick paint coating to total thermal resistance was found to be negligible.

A new approach for metering thermal contact conductance by using existing thermal analysis equipment was verified, and these values were measured for the first time. This information can be used in lining design, and the discovered method can be deployed in the future to study similar cases. What remained was a need to study both surface metrology and thermal contact conductance, since surface and thus contact quality apparently control the thermal contact conductance at the interface. There is also a need to compare thermal conductivity, and hence thermal conductance results achieved by laboratory-scale transient methods, and results achieved by steady state methods, since in practice the heat transfer in the refractory lining is more stationary.

Further information

KEY PUBLICATIONS:

V. Matikainen, H. Koivuluoto, P. Vuoristo, Microstructural Characteristics Of Different Cr_3C_2 Coating Compositions Sprayed with HVAF Process, The Twenty Eighth International Conference on Surface Modification Technologies, Valardocs, 28, 2015, p. 77–87

J. Laurila, P. Vuoristo, O. Tuovinen, M. Uusitalo, Surface Reactions of Single Crystal Diamonds with Chromium Containing Nickel-based Braze Materials, IBSC 2015, Long Beach CA, USA.

J. Kiilakoski, M. Lindroos, M. Apostol, H. Koivuluoto, V.-T. Kuokkala, P. Vuoristo, Characterization of High-Velocity Single Particle Impacts on Plasma-Sprayed Ceramic Coatings, Journal of Thermal Spray Technology, 25(6), 2016, p. 1–11.

M. E. Cura, V. K. Singh, P. Viitaharju, J. Lehtonen, S.-P. Hannula, Pulsed Electric Current Sintered Cr_2O_3-rGO Composites, Key Engineering Materials, 721, 2017, p. 419–424.

D. Fantozzi, V. Matikainen, M. Uusitalo, H. Koivuluoto, P. Vuoristo, Chlorine-induced high temperature corrosion of Inconel 625 sprayed coatings deposited with different thermal spray techniques. Surface and Coatings Technology, 2017, 11 p., published online.

CONTACT PERSONS:

Jarkko Kiilakoski, Heli Koivuluoto, Jussi Laurila, Erkki Levänen, Ville Matikainen, Jussi Silvonen, Petri Vuoristo,Tommi Varis, Davide Fantozzi/ Tampere University of Technology; Tomi Suhonen/VTT; Simo-Pekka Hannula/Aalto University; Ulla Kanerva, Olli Tuovinen, Mikko Uusitalo/ Valmet; Sauli Seppänen/Abloy; Jukka Koivunen/Virtasen Koneistamo; Jukka Finne/Kuopion Konepaja; Jussi Larjo/Oseir; Timo Rantala/TKM TTT Finland Oy; Kari Vierimaa, Jussi Hellman/Metso Flow Control Oy; Mari Lindgren/ Outotec Oy; Seppo Heiskanen, Ahti Ekdahl/Kokkola LCC Oy; Juha Rintala/Telatek Service Oy

PARTICIPANTS:

Valmet Technologies Oy, Metso Flow Control Oy, Millidyne Oy, Oseir Oy, Abloy Oy, Kuopion Konepaja Oy, Virtasen Koneistamo Oy, Telatek Service Oy, Kokkola LCC Oy, Outotec Oy, TKM TTT Technology Oy, Tampere University of Technology (TUT), VTT, Aalto University

Kim-Niklas Antin/Aalto University
Mika Paajanen/VTT
Tapio Fabritius/University of Oulu
Heikki Kettunen/Valmet Technologies

Damage detection and intelligent sensing

Summary of the project's motivation and achievements

The *Damage detection and intelligent sensing* part of the project was created to give answers to a very important question in industrial applications: how to obtain information on a mechanical event in an electronic form. This general description of the problem can be best understood using some practical examples. For instance, monitoring the condition of a safety-critical mechanical component, such as those found in elevators, requires some sort of signal that can be measured, analyzed, and stored. Similarly, monitoring of process conditions is essential for producing high-quality products, such as paper and cardboard. It is clear that these measurements should be sensitive enough to give an early warning if something is wrong. In addition, the operator of a machine can introduce a mechanical input, for example by touching a surface, and this input should be transformed into an electronic signal that controls the machine.

Several new implementations of damage detection and sensing were developed during the project. This was achieved by designing better sensor materials that are easy to apply and are able to operate at high temperatures, as well as dedicated detection systems tailored for specific applications. Extensive testing in the field of detection and sensing has significantly improved the competence and understanding to develop new methods and materials for specific applications. The benefits and drawbacks of each system have been established and the factors affecting performance are understood.

Better sensor materials and several dedicated detection systems developed.

Key results and impacts

Non-destructive evaluation of composites

Composites are materials that consist of two or more constituents with differing properties. The performance of the composite is fully dependent on the interplay of the individual constituents. For example, in fiber reinforced polymer (FRP) matrix composites, the strong fibers carry the load while the adhesive matrix binds and protects the fibers. In addition, protective coatings can be applied. Because of the heterogeneous composition inherent in FRPs, they have characteristic behavior and failure modes, which are different compared to homogeneous structural materials such as metals. For example, the fibers can fail, the matrix can fail, or the fibers can debond from the matrix. Furthermore, interply failure of laminated structures can occur, called delamination (Figure 1). Due to the numerous possible loading cases, and a multitude of defects and failure modes, assessing the damage state and performance of composites is a complex task.

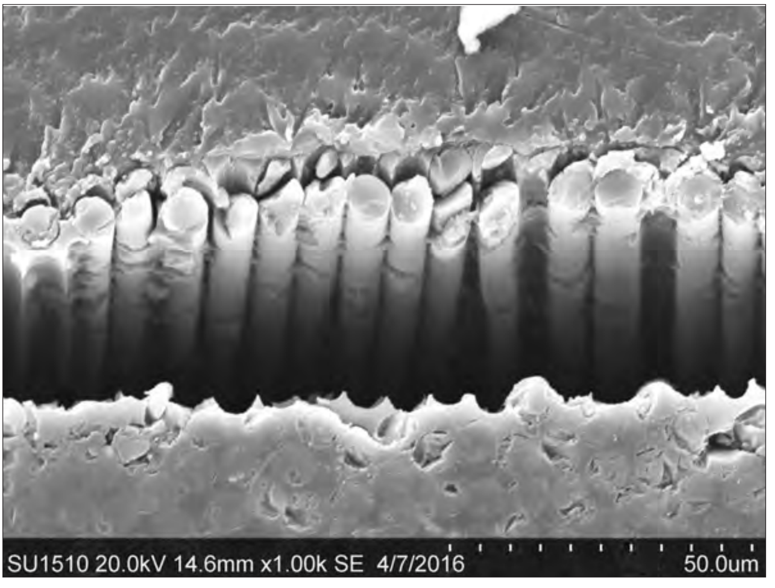


Figure 1. Scanning electron microscope image of the cross-section featuring the delamination plane. The rods are carbon fibers tied together with a polymer matrix

The general principle of non-destructive evaluation (NDE) is simple. An input of energy is needed and the output is monitored. In order to detect a defect, two requirements must be met. First, there must be contrast between the damaged state and the intact (reference) state. Second, sufficient spatial resolution must be achieved to see local changes. However, each application is different and the detection equipment and data analysis are continuously being developed. The project started with a general investigation of the capabilities of current and known methods. Due to the multiple constituents in FRPs, anisotropic properties, protective coatings used, and underlying substrates, many of the methods developed for traditional structural materials, meaning metal alloys, are not suitable.

It also became clear that matrix damage, fiber damage, and residual strain measurement often require separate detection methods. The increased understanding of the behavior of the composite during standard inspection led to focused development work on a few of the most promising techniques.

Company impact

"We constantly need to improve our production efficiency and product quality as we are increasingly working with global OEMs that demand robust high-quality manufacturing. NDT methods help us on production lines to measure both quality and efficiency. In this research project, we were able to focus on the possible manufacturing defects and NDT methods that could help track them when defects are not visible. In addition, the understanding of initial defects and their propagation has helped us to set criteria in our quality control."

***Mikko Lassila,** group sales development manager, Exel Composites*

Developing a damage detection system for composites is challenging, due to the different damage types that can occur. However, developing new methods in laboratory conditions requires controlled specimens for testing. Controlled artificial defects that are used are drilled holes, machined V-grooves, sub-critical mechanical loading, and drop-weight impact damage (Figure 2). These defects are used to assess the capabilities of the tested detection method. Once the method has been optimized, more realistic defects can be introduced. Such samples include accelerated tests in realistic conditions (delamination damage) and manufacturing imperfections produced on the actual production line (voids, improper cure of resin system, residual strains). Extreme hot/wet conditions have also been proven to reduce the fatigue performance of fiber-reinforced polymer composites, lowering matrix properties and leading to delamination.

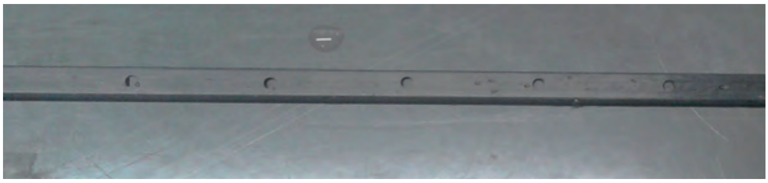


Figure 2. Drilled flat-bottomed holes for testing the resolution and contrast of various inspection methods

Ultrasonic inspection method has already been adapted by KONE for characterization and quality control purposes.

Elevator ropes used by KONE and made from composite materials are a good example of an application in which non-destructive evaluation is needed for safe operation. One of the methods adapted for this type of product is ultrasonic testing (UT). Ultrasonic testing is and has been the most used NDT method for composites, because their application is critical for safety components. The method relies on sending acoustic waves inside the component in the range of 1–20 MHz and measuring the intensity of the reflected signals. The received signals are generated at points of inhomogeneity in the material, where the acoustic impedance of the excitation wave changes. This means that composite-specific defects such as delaminations and voids can be detected (Figure 3). Phased Array UT is the next step from traditional ultrasonic imaging, in which multiple transducers are fired in a varying sequence to create a focused wave front that greatly improves the resolution of the method. The use of multiple transducers also enables inspection of larger areas with a single scan. Due to their favorable orientation in relation to the ultrasonic excitation wave, delamination can easily be spotted in the rope. The downside of the method lies in the fact that, to ensure adequate transmission of the signal to the inspected component, a coupling medium, most often water or gel, is needed for inspection. This makes it more challenging to adapt the technology to elevator conditions. However, the ultrasonic inspection method has already been adapted by KONE for characterization and quality control purposes.

Company impact

"NDT methods have given us deeper understanding of carbon-fiber reinforced plastics and thus played an integral role in improving our product. In long products, such as elevator ropes, assessing the worst-case performance is a tedious task. Ultrasonic testing made it possible to direct our testing to imperfect parts of the rope and helped us evaluate the worst-case performance with confidence."

***Mika Juntunen,** senior specialist, KONE*

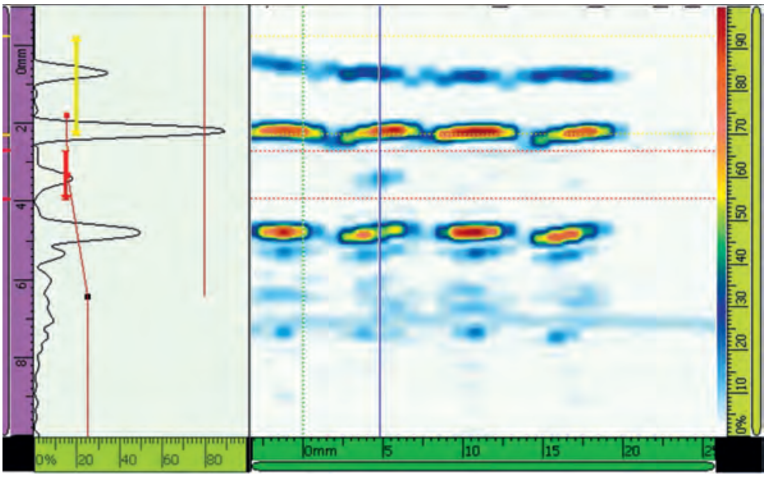


Figure 3. **Ultrasonic A- and C-scan image of a detected anomaly in the mid-plane of one of the CFRPs (carbon fiber reinforced composite). The top four red bars represent the top echoes from the CFRPs, and the lower red bars represent the echo from the bottom of the CFRPs. During the implementation of UT, it was necessary to characterize these findings more precisely, which is why samples were cut and sent to the University of Jyväskylä for 3D microtomography (μCT)**

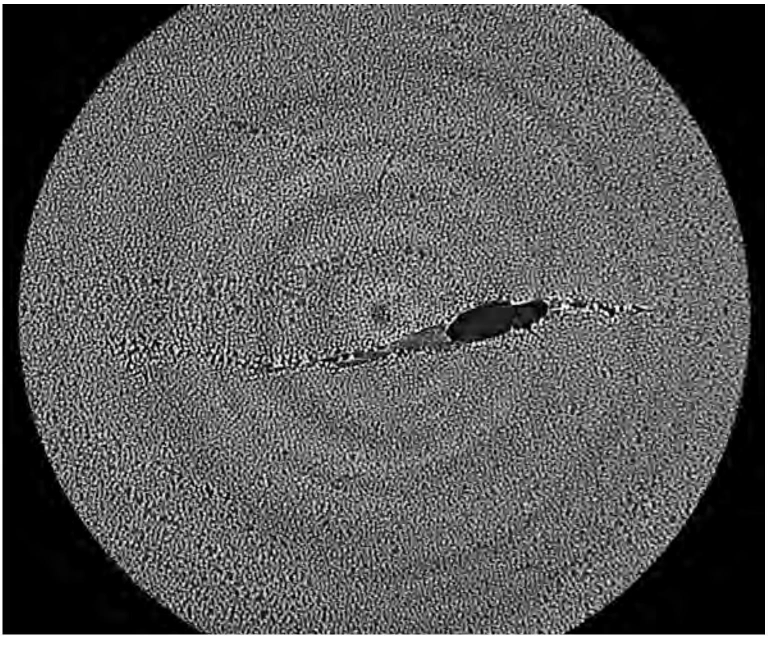


Figure 4. **A high resolution image of the UT anomaly seen in Figure 3. Due to the physics of the imaging device, the CFRP appears circular. The white circles propagating from the middle are imaging artefacts. The fiber ends are seen as grey round profiles inside the darker matrix area. In the center, we clearly see a void, which is trapped air inside the CFRP**

Eddy current testing is a good method of detecting local fiber breaks. The results of laboratory-scale experiments are being transferred to a system capable of damage detection in field conditions.

Ultrasonic inspection is sensitive to interfaces perpendicular to the wave propagation, and good results were achieved when looking for delaminations and voids. However, fiber breaks are usually distributed over an area, and the discontinuities are at a less favorable orientation to the ultrasonic probes. Using the electromagnetic properties of carbon fiber enables the use of **eddy current testing**. Eddy currents are a result of an alternating current in a coil, causing a changing magnetic field, which in turn causes induction of circular currents (or eddies) in a conductive material. The induced currents cause a magnetic field themselves, which affects the electrical impedance of the coil (mutual induction). Monitoring the impedance changes gives an indication of the changes in conductivity and the formation of eddy currents (Figure 5). Broken fibers hinder the path of eddy currents and affect the local conductivity of the material.

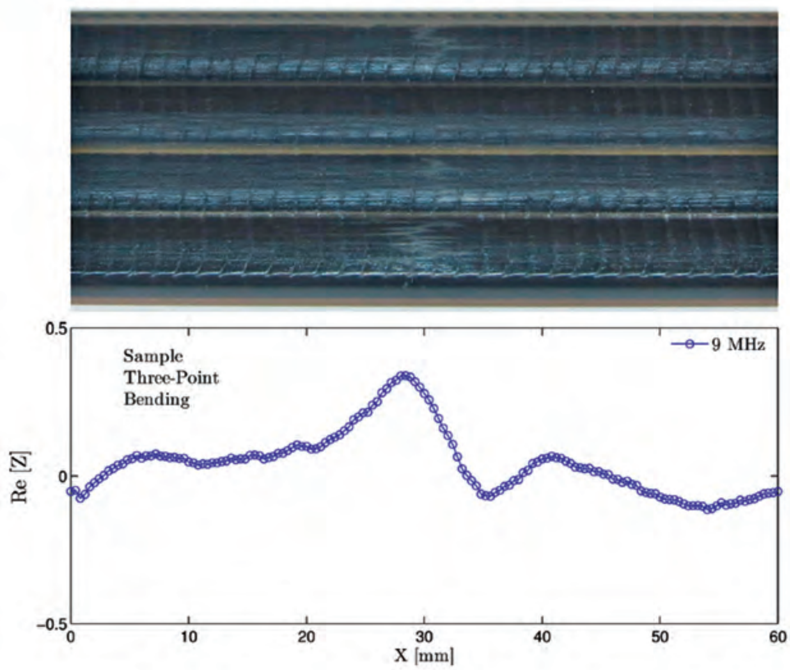


Figure 5. **Three-point bent sample with broken fibers in the middle. A change in impedance is seen in comparison to the intact surrounding material**

Another example of non-destructive evaluation is the **use of optical fibers to measure residual strains in composites**. Residual strains arise during manufacturing and can lead to debonding from a substrate, delamination, or lowered fatigue life. The roll covers used by Valmet in their paper machines are critical for the reliable production of high-quality paper. Residual strains can degrade performance and cause sudden failures during operation. Quantifying residual strains non-destructively in composites is not as easy as for homogeneous crystalline materials, where x-ray diffraction can be used. Embedded strain sensors, such as optical fibers with Bragg gratings, provide a means to monitor strain levels in composites during and after the manufacturing process (Figure 6). The work done in this project using sensors tailored by the Institute of Nanostructures, Nanomodelling and Nanofabrication (Portugal) showed that significant residual hoop strains (0.2%) remain in the top cover after processing. Being aware of the magnitude and direction of the strains makes it possible to take them into account during design, manufacture, and modeling. The sensors can also be used to monitor any structural changes that occur in the material during use.

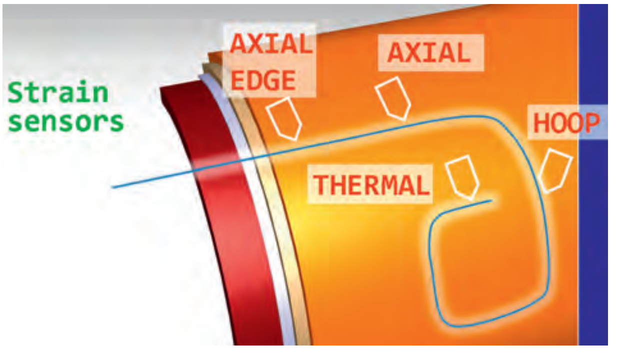


Figure 6. Layered structure of a roll cover used in paper machines. Optical fibers measure the strains in various directions and locations

Several new detection systems were developed to monitor composite components. Monitoring makes it possible to guarantee safe operation, as well as to save costs by reducing unnecessary or sudden maintenance. The impact is significant, because it enables the use of the full potential of high-performance composite materials. In other words, significant material and energy savings can be made without compromising safety and reliability. However, detecting and localizing damage are the first steps in condition monitoring and evaluation. Determining the effect of the observed defect and the subsequent action are also required. Non-destructive evaluation of the effect of a defect needs to be based on modeling, since the actual component in use cannot be tested to failure and a completely identical test specimen is impossible to produce. Therefore, models predicting the remaining life and performance are needed, in addition to the detection methods developed in this project.

Intelligent sensing

Sensing is similar to non-destructive evaluation. In both cases, a signal is required to tell the user something about the changed state of the component. The new state can be a random occurrence of damage, a variation in process parameters, or an input from the user, such as by touch. In all cases, the mechanical change in state needs to be converted into an electronic signal for further manipulation. For example, embedding electromechanical films into paper rolls enables the monitoring of nip pressure distribution (Figure 7). Touchscreens are another good example of an application that uses the conversion of a mechanical event into an electronic signal.

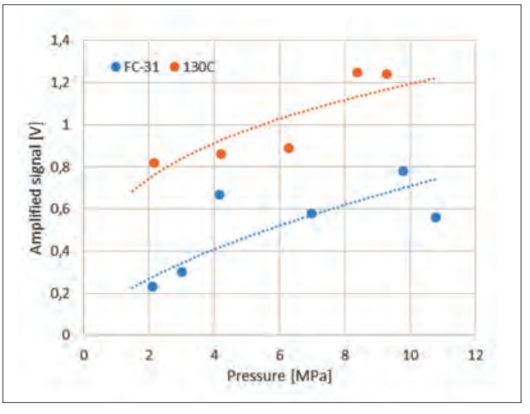


Figure 7. **Amplified signal amplitude against application pressure for developed EM film sensor material without heat treatment and with 130°C short-period (a few hours) heat treatment**

New polymer materials for electromechanical sensing at elevated temperatures were developed. The main targets and motivation for the project were to form an overall thermally durable cellular film by combination of suitable plastic grades and micro/nano-fillers, and to develop adequate nano-dispersion and optimal cellular film structure in industrial-scale production. New polypropylene (PP), cyclo-olefine (COC), and polyhedral silsesquioxane (POSS) based electromechanical (EM) films were produced, which can withstand long-term use at least up to 110°C, medium-term use at least up to 130°C, and short-term thermal shocks at least up to 220°C. The developed film has also passed preliminary testing for thermally more demanding industrial application at Valmet Technologies Oy. The major innovation potential is based on the EM function that can be adopted with fewer processing steps, and thus more cost effectively, for bulk plastic and thermoset elastomer structures.

New electro-mechanical sensing film – a robust and cost-efficient solution for industrial applications.

Piezoelectric thick film inks were also developed. The best inks obtained a record-breaking piezoelectric charge coefficient d31 of -25-40 pC/N for steel substrate and as high as -60 pC/N for polymer substrates. The results have been obtained by systematic research of the electromechanical properties, and modeling with respect to the processing parameters and surface modifications of the piezoelectric ceramic filler particles. The results enable realization of high-sensitivity sensor elements on flexible substrate (Figure 8) or directly applied sensors in, for example, steel structures for large surfaces for different types of monitoring purposes and IoT solutions.

Piezoelectric thick film inks with record-breaking piezoelectric charge coefficient developed.

Figure 8. **Piezoelectric ink (light yellow) printed on PET film with top and bottom electrodes (gray)**

In addition, **thermoplastic piezoelectric composites** to withstand elevated temperatures were developed and tested. The developed material enabled the realization of sensor elements by injection molding and by extrusion, enabling series production or even continuous fabrication of long sensor ribbons. Such ribbons can be applied on, for example, curved surfaces (Figure 9) as long sensor arrays, as cost-effective and flexible solutions for different types of force and pressure detection for advanced process and condition monitoring.

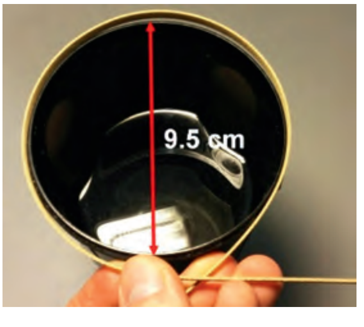


Figure 9. Bent extruded piezoelectric composite ribbon

An **autonomous piezo element-based pressure measurement system** (Figure 10) with wireless data transfer was developed and demonstrated in order to exploit the potential of the developed sensor technology. The demonstrated concept was based on the fact that a piezo element generates an electric signal once it is stressed mechanically. By adding the printed antenna directly to the piezo element, the mechanical deformation of the sensing element caused by pressure change can be directly converted to an electromagnetic signal. That signal can then be transferred wirelessly to the secondary antenna without any additional electronics. Once transmitted to the secondary antenna, the pressure signal from the piezo element can be read remotely.

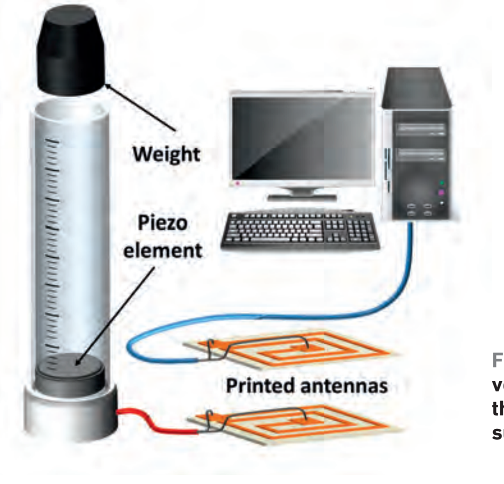


Figure 10. Schematic of the developed system to demonstrate the autonomously working pressure sensor system

The accumulated processing and material know-how can be utilized for the development of injection-molded parts in numerous sectors like ICT: durable user interfaces like keyboards and touch screens; consumer goods: white appliances and household electronics parts made of bulk plastic like touch-sensitive surface and control panels for washers, coffee machines, televisions, and microwave ovens; transport: structural vibration and condition monitoring in airplanes, driver-activity monitoring integrated in the seat structure in cars and utility vehicles, and other switches, keyboards, and touch-sensitive surfaces in interior parts. Additionally, large-area touch-sensitive "skins" for robots can be envisioned by utilizing these simple but intelligent bulk plastic parts. The EM function can be integrated to add value to tubes/hoses (flow monitoring), belts (load and presence monitoring), appliances (touch-sensitive parts to become user interfaces), flooring (medical use for heartbeat, breath rate, seizures, and activity monitoring),

Autonomous piezo element-based pressure sensors have huge application potential.

and shoes (activity and posture monitoring). Globally, there are several thousand paper and board machines. Each of these machines could benefit from 5 –10 intelligent rolls with embedded sensors. Moreover, the intelligent rolls could also be used on stretching rolls in plastic film lines or in other production lines where smart rolls could be utilized. This will thus have an impact on both paper, plastic, and other roll production lines, making them more competitive and resource efficient. Autonomously working sensors systems are a very interesting concept to be utilized in industrial applications, since the piezo element and the antenna can be embedded into machines.

Further information

KEY PUBLICATIONS:

Antin, K-N. Damage Detection in CFRP Components Using DIC. 2016. Advancement of Optical Methods in Experimental Mechanics 3, 57–62.

Näreikkö, A. 2015. Mechanical testing of unidirectional carbon fiber reinforced plastics. Master's thesis. Aalto University.

Several patents have been filed in SP2-T1. Journal publications are on the way.
T. Siponkoski, M. Nelo, H. Jantunen, J. Juuti, The electromechanical properties of printable P(VDF-TrFE)-PZT composite with very high piezoelectric coefficient, Advanced Functional Materials (to be submitted).

T. Siponkoski, H. Jantunen, J. Juuti, Low-temperature curable high-performance piezoelectric ink for different substrates, Composites Science and Technology (to be submitted).

J. Tolvanen, J. Hannu, J. Juuti, H. Jantunen, LCP-PZT polymer composite strips for high-temperature sensor applications, Electronic Materials Letters (to be submitted).

Vilmi, P, Sorvoja H. and Fabritius T. Printable autonomously working activity sensor with wireless data transmission. Scientific Report (to be submitted).

CONTACT PERSONS:

Kim-Niklas Antin/Aalto University, kim-niklas.antin@aalto.fi
Mika Paajanen/VTT, mika.paajanen@vtt.fi
Tapio Fabritius/University of Oulu, tapio.fabritius@oulu.fi
Heikki Kettunen/Valmet Technologies, heikki.kettunen@valmet.com

PARTICIPANTS:

Aalto University, Componeering, DEKRA Industrial, Exel Composites, KONE, Valmet Technologies, VTT, Emfit, Screentec, University of Oulu

LIGHT MULTIFUNCTIONAL HYBRID STRUCTURES P3

Marko Antila, Tomi Lindroos, Jukka Tanttari/VTT
Juhamatti Heikkilä, Marke Kallio/Metso
Ari Karjalainen/Machinery Acoustics
Lasse Kinnari/NMC Cellfoam

New materials for noise and vibration control

Summary of the project's motivation and achievements

Restrictions and legislation, as well as increased demands for safety and productivity, are setting new requirements for the design of materials and structures. For example, mobile machinery should be able to operate in an urban environment without disturbing the surrounding area. In the worst case, the permitted operation time of machinery is limited, if required noise and vibration levels are not reached. This directly affects the productivity and competitiveness of the industry.

The circular economy requires crushing of waste materials on site – urban environments set high requirements for noise control.

For the circular economy, on-site processing of materials is mandatory in many cases. In the case of recycling of construction materials by crushing, on-site processing provides benefits for the customer and the environment by minimizing traffic. At the same time, the contractor's margin is improved. Legislation is setting restrictions in Finland, and operating less than 300 meters from residential and cottage buildings calls for specific measures to certify that permitted daytime noise limits are not exceeded. Noise control, in addition to dust control, is critical. In addition to legislation, citizen experience and social acceptance are important.

Company impact

"Today, our customers are facing more and more demanding environmental requirements in their crushing and screening operations. During the Hybrids project we significantly improved our understanding of crushing noise and learned how to reduce the environmental impact of our products."

Juhamatti Heikkilä, manager, product safety, Metso Minerals, Inc.

Figure 1. **Crushing station equipped with prototype noise shield operating in the middle of a residential area**

In this project, the noise-control system and noise reduction have been approached from the perspective of shielding, also improving dust protection. In the project, it has been confirmed that the parallel process that serves as noise reduction is also suitable for the assessment of environmental noise from nearby residents in terms of annoyance. The process now improves the audio quality indicators or their combinations, instead of just noise emission reduction.

The main target of the project was to achieve significant improvements in noise and vibration control through the application of multifunctional low-weight hybrid structures, as illustrated in Figure 1. The main focus was on the development of add-on and multipurpose noise and vibration control concepts and solutions. A link between perceived noise and the control strategy was established. Furthermore, understanding of the environmental noise characteristics and audible models was developed. The solution concepts are generic and applicable to other machinery as well.

Multifunctional low-weight hybrid structures for noise control.

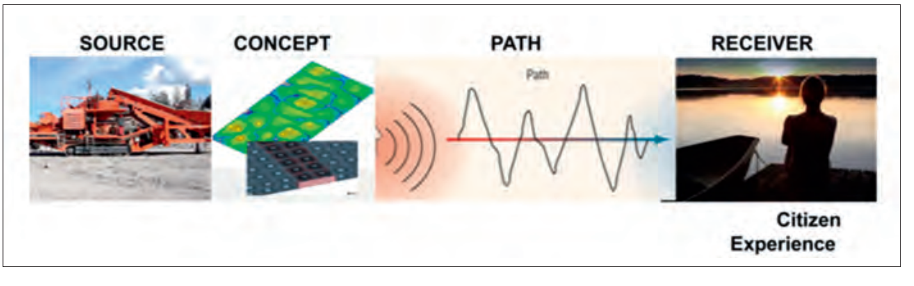


Figure 2. **The concept: controlling noise from source to citizen**

Motivation

In the crushing of hard minerals, large forces are needed in order to break the rock. Inevitably, the forces fluctuate in the crushing process. These fluctuating forces cause dynamic excitations. The crushing and screening equipment surfaces and disintegrating rocks radiate noise. In urban areas, crushing processes are restricted to certain times of the day due to noise pollution. Consequently, improvements in noise control are sought.

Comprehensive understanding and solutions for noise control – from source to citizen.

There have been a lot of attempts to reduce crushing noise. However, noise reduction solutions should not complicate or compromise the actual crushing process. The noise reduction solutions should be easy to achieve through add-on components or should be elementally integrated into the equipment. Noise reduction can also be achieved through equipment redesign. The redesign can, obviously, enhance the actual crushing process. However, the latter measures are not within the scope of the study at hand.

Key results and impacts

Groundbreaking results were achieved with **new crushing machine concepts** and in all three research areas: **sound absorption, sound insulation**, and **sound quality**. The successful noise control solutions developed in this project can lead to totally new products for the mining and construction business, and can benefit other industry segments as well.

For **new crushing machine concepts**, simulations, structures, and measurements were developed, and prototypes were tested and verified in a real crushing process by *Metso Minerals*, in co-operation with *Machinery Acoustics*.

New crushing machine concept.

For **sound absorption and insulation**, developed vibro-acoustic modeling and characterization tools for materials and structures act as a basis for developing multipurpose, hybrid noise-control solutions. The hybrid material structures were studied and developed for this purpose. The best solution concepts were tested as prototypes in the project. VTT was mainly responsible for this research, in co-operation with NMC Cellfoam. NMC Cellfoam also developed their own know-how related to material properties.

For sound quality, the main result is establishing a virtual platform for a fast development process and optimized solutions. The platform enables the combination of separate research results in one tool, to evaluate how different noise-controlling attempts affect perceived noise. Virtual enclosure is the key element of such a platform. The virtual enclosure concept combines absorption material results with results of lightweight periodic structures, and audible and measurable noise in the audible model. With that, the citizen experience can be evaluated and the evaluation results can be fed back into material development to improve and optimize the situation. VTT created the virtual platform and virtual enclosure concept.

In co-operation with the partners, Machinery Acoustics developed expertise in the fields of citizen experience, social acceptance of noise, and sound quality to the level of commercial service. The main customers are expected to be among the DIMECC HYBRIDS and BSA program participants.

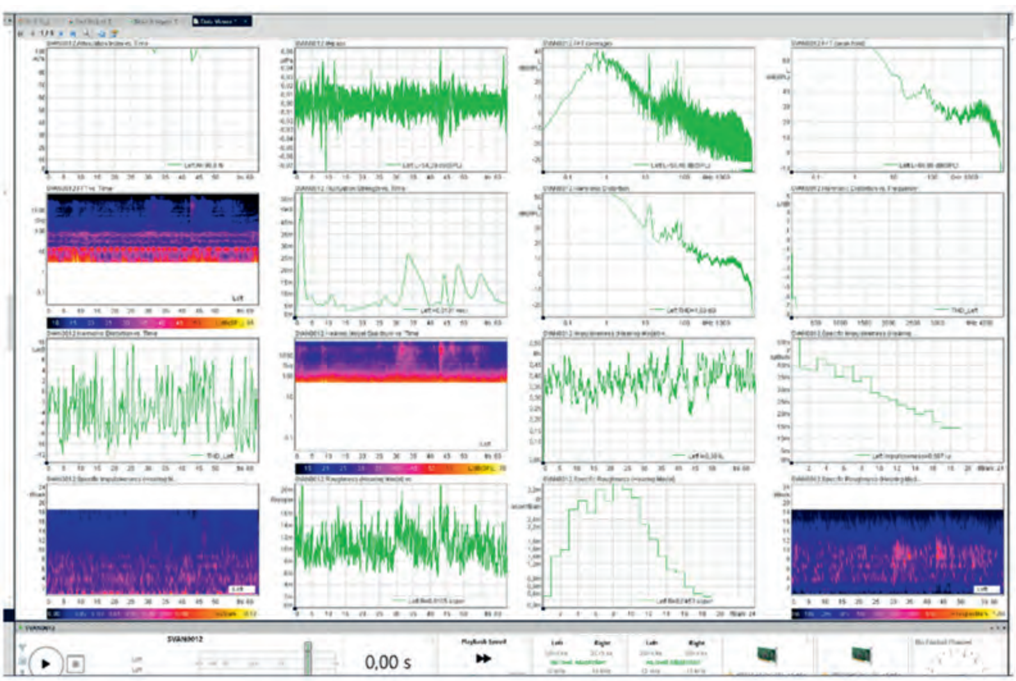


Figure 3. An example of Machinery Acoustics measurements using their expertise and commercial software

Sound absorption

The microstructure of acoustic materials mainly determines their acoustic properties and performance. For that, new acoustic material solutions were developed and optimized. Tools to predict interdependency between the material microstructure, macroscopic parameters, and acoustic performance were created. Such tools were utilized to improve knowledge of the relations between microstructural features and absorption properties, and finally acoustic performance.

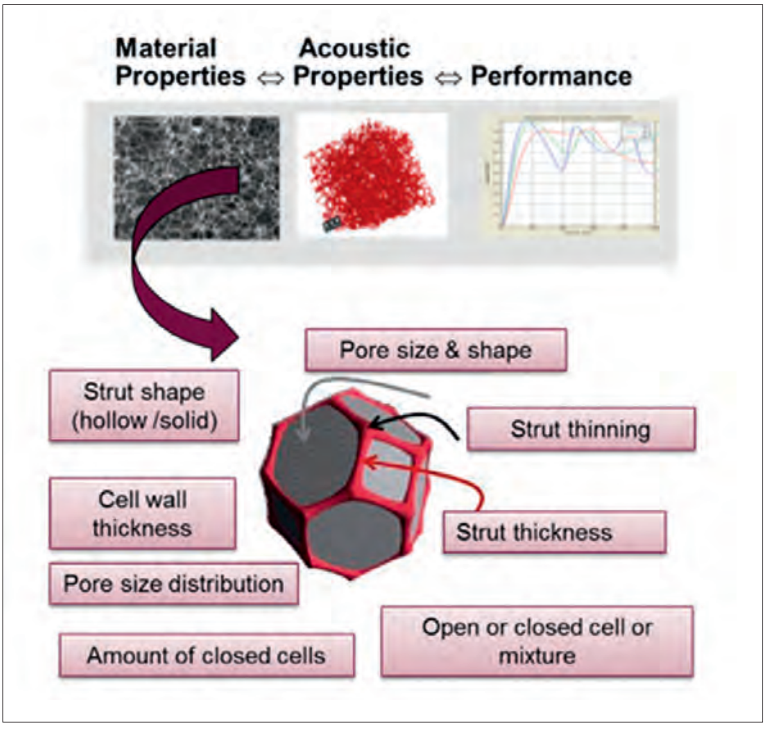


Figure 4. Novel virtual tools created for microstructural features

The feasibility of commercial software (GeoDict) to predict acoustic parameters from an absorption material microstructure by utilizing 3D imaging techniques was studied. In addition, the software's applicability as a tool for defining the interactions between the absorption material microstructure, acoustic parameters, and performance was studied. Software feasibility validation was done using two example cases for a typical sound absorption material, melamine foam. The simulated results were compared to the measurements results.

In the first case, a 3D tomography image of melamine foam was imported to the software, and in the second case, the software was used to create the virtual foam model from the identified geometrical parameters of scanning electron microscopy micrographs of the melamine foam. In both cases, the software was used to calculate the acoustic parameters, and the results were compared to the measurement results. A more detailed evaluation of the commercial software feasibility is in the proceedings of the Akustiikkapäivät 2015 conference (Karhu et al. 2015).

The multi-scale computation method was implemented for acoustic purposes. The method controls the chain of parameters, including the relations between the microscopic, macroscopic, and acoustic parameters, and the performance of sound absorbing materials. The chain of parameters is presented in Figure 5.

In the frequency-dependent direct numerical approach, the acoustic parameters are directly computed from the micro-scale parameters using Comsol. In the static hybrid numerical approach, the macro-scale parameters are computed from the micro-scale parameters using Comsol, and the corresponding acoustic parameters are further computed using MATLAB. The acoustic performance is computed using MATLAB.

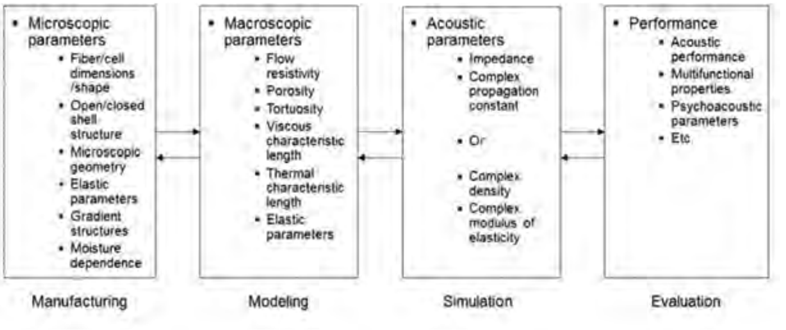


Figure 5. Chain of parameters in controlling the performance of sound-absorbing materials

The multi-scale computation methods presume periodic structures consisting of similar unit cells and periodic boundary conditions between individual unit cells. The method has been tested on three unit cell constructions of spheres, as presented in Figure 6. The acoustic performance (absorption coefficient) of the constructions is presented in Figure 7, calculated in this study, and presented by Lee, Leamy, and Nadler (2009). The similarity is obvious.

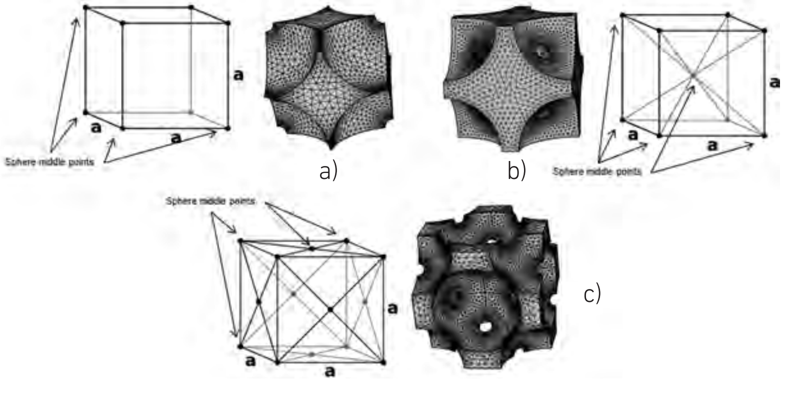


Figure 6. Test computation unit cell constructions: a) simple cubic (SC), b) body-centered cubic (BCC), and c) face-centered cubic (FCC)

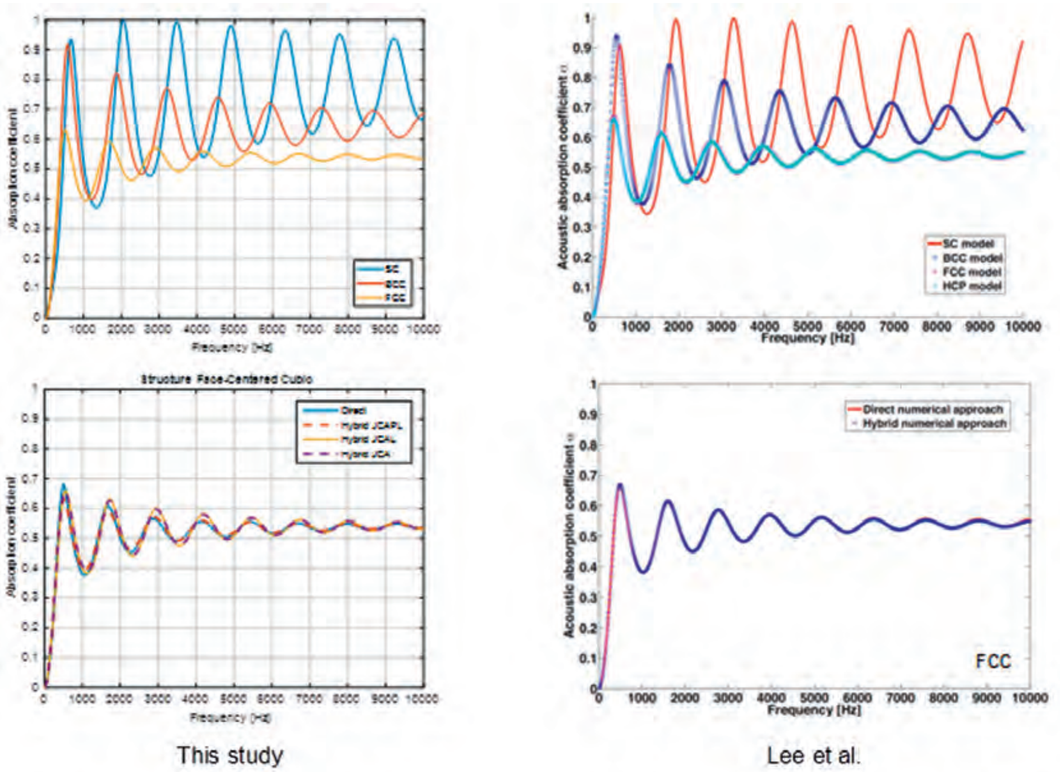


Figure 7. **Absorption coefficients of test constructions. 100 mm sample with rigid boundary, normal sound incidence**

The main benefit of using multi-scale methods in acoustics is that the acoustic performance (i.e., the absorption coefficient) can be evaluated by simulation without measurements. Furthermore, the acoustic performance can be enhanced by changing the micro-scale parameters in simulations. Thus, no trial-and-error test samples are needed, and the performance can be tuned at desired frequencies. The implemented multiscale model has been used in optimizing the sound absorption properties of sandwiched gravel layers on the ground.

Sound insulation

Small mass and high stiffness are eligible properties of structures used in machinery and vehicles. However, these properties, namely high specific stiffness, are potentially disadvantageous from a vibro-acoustic and noise control point of view. High specific stiffness of a panel means a high propagation speed of flexural waves. This, in turn, accounts for efficient sound radiation and poor insulation properties.

Conventional acoustic enhancement of lightweight structures uses damping layers and extra mass, for example. In this work, new solutions have been sought to enhance the acoustic properties of lightweight structures while maintaining high specific stiffness. Special attention has been given to sandwich structures.

A sandwich structure is composed of two thin, stiff skins and a light, relatively thick core. Insulation properties are largely governed by the mechanical properties of the core. Modification of the core offers many possibilities to gain better properties. One solution studied is the implementation of tailored patterns of voids in the core. Carefully designed periodic patterns (Figure 8) can be used to decrease the speed of flexural waves and enhance insulation at high frequencies.

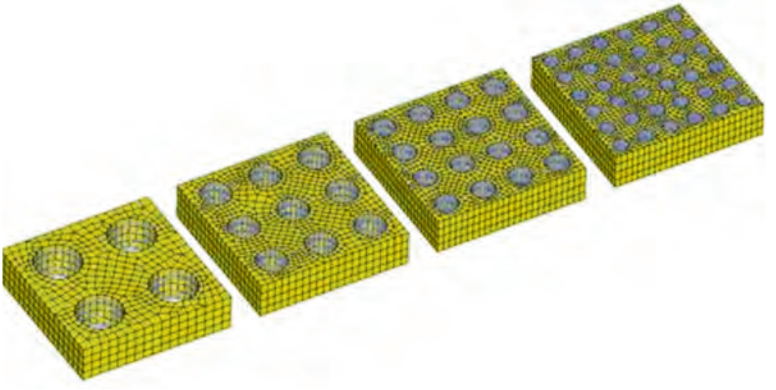


Figure 8. **Core void patterns in a periodic cell of a sandwich panel**

A new, emerging field of research is the application of locally resonant acoustic metamaterials (LRAMs) for vibro-acoustic purposes. LRAMs provide new, passive, integrated possibilities based on wave-filtering using bandgaps. A bandgap, or a stopband, means that structural waves at certain frequencies do not propagate in a structure. Instead, they are rapidly attenuated. The effect is not based on increased damping. It is based on the calculated utilization of localized resonances to counterforce the propagating waves. With limited modifications (voids, filled or not filled with other materials) to the sandwich core, it may produce strong filtering effects.

Optimal sandwich structures utilizing metamaterials and modeling.

One challenge is the vast number of possible design solutions. We have studied the automatic design of LRAM structures for a given bandgap frequency and developed optimization tools. For example, resonator parameters and locations in a structure are varied to maximize the depth of a bandgap.

Optimal sandwich structures to generate bandgaps of the frequency response functions (e.g. mobility) are studied by a software system combining optimization algorithms and structural analysis. Harmonic force excitation is applied to a point or area in a sandwich panel or beam. The response is observed at a desired point. The objective function to be minimized is the maximum magnitude value of the response in a chosen frequency range or in several ranges simultaneously.

The optimization problem is formulated as an equivalent min-max problem. The computational tool for the general approach to different problem types (including arbitrary geometry, structural periodicity, and the multicriteria approach) is based here on MATLAB software combined with ABAQUS finite element software for structural analyses. The design variables include a wide variety of material and geometric parameters, such as the main dimensions, thicknesses, resonator parameters and locations, anisotropic material values, and shape parameters. The feasible set is defined by the variable bounds and relevant constraints on the design variables and system functions.

$$\min_{x \in \Omega} f = [f_1 \cdots f_k]^T \qquad x = [x_1 \cdots x_n]^T$$

$$\Omega: \quad h_i(x) = 0, i = 1, \ldots, r$$

$$g_i(x) \leq 0, i = 1, \ldots, s$$

$$\underline{x}_i \leq x_i \leq \overline{x}_i, i = 1, \ldots, n$$

f – objective function (scalar or vector)
Ω – feasible set
x – design vector (continuous or integer/discrete)
h_i, g_i – constraint functions

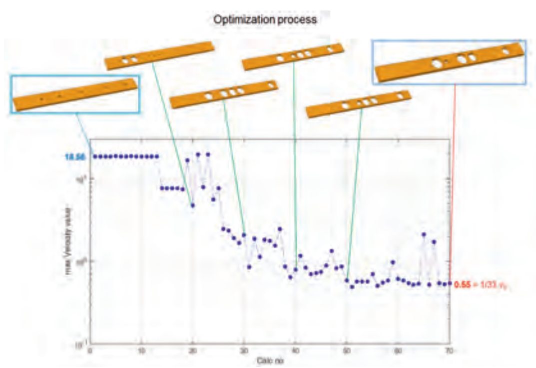


Figure 9. General optimization problem and numerical optimization process of a sandwich panel with five circular holes in the core. The objective function is a point velocity and all the function generations during the process are shown (the objective function value of the approximate optimal structure is 1/33 from the initial value)

There are a number of different solution methods for general nonlinear optimization problems. The algorithms used here exploit the sensitivity analysis of the system functions, and especially the SQP (sequential quadratic programming) method. A benefit of the derivative-based methods is the accuracy and a reasonably fast convergence. The main disadvantage where structural analysis is concerned is the quite expensive sensitivity analysis, which may, for large problems, be a serious problem. In the present type of sandwich bandgap calculation, the instability of the numerical solutions is also a challenge. Small variations in the design vector can cause large fluctuations in the response, due to the many close natural modes and the inaccuracy of the derivative calculation.

After the need for bandgaps for acoustic or other reasons is identified, it is often advisable to try to design a structure that is easy to manufacture but that still fulfils all the problem requirements. For that purpose, one example choice here is a sandwich panel with uniform faces and circular holes in the core, which is also favorable for optimization, with rather few design variables (locations and radii of the holes). In Figure 9, the general optimization formulation and the progress of the numerical optimization process in a sandwich with five circular holes in the core are presented.

Periodic structures are solved by targeting the optimization of the basic cell and repeating that for the desired number of times. In Figure 10, an example with four cells in a 2 x 2 format is shown. The previously determined bandgap location is 775 Hz – 785 Hz within the 0 Hz – 1 kHz total range. As a result of optimization with at most 5 circular holes in the core, the maximum response value in the bandgap range is 1 % of the value of the structure with no holes. Conducted tests shown that the numerical optimal solution is rather sensitive to design value variation.

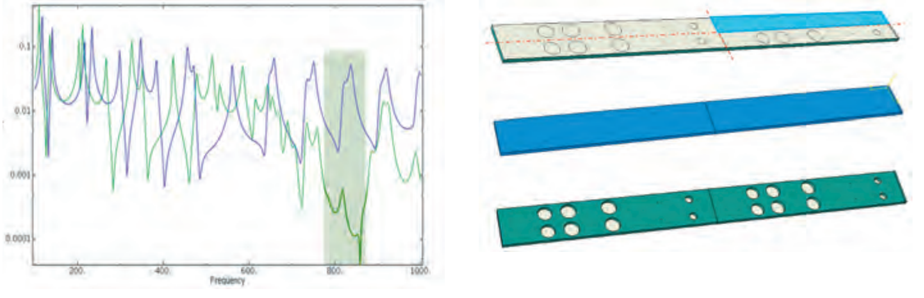


Figure 10. Bandgap optimization of a 2x2 periodic sandwich structure. Blue: initial structure with no holes; green: optimized structure with at most five circular holes

Typically, the optimization process results in a 95% to 99% descent from the top value of the frequency response function in the desired frequency range. The results show that even with rather simple structural modifications, like making circular holes in the core of the sandwich panel, a bandgap-type solution can be achieved. If more advanced manufacturing methods are available, the design space can be enlarged and the potential of the mathematical optimization process as a design tool increases further.

While the presented approach to shape optimization is implemented with fixed topology, general topology optimization with the possibility of topology change during optimization has also been studied in this project. In this approach,

New tools and concepts created for tailoring lightweight, noise-critical structures.

the virtual density of each element in the finite element model is a design variable, and that demands different methods for sensitivity analysis from those in traditional shape optimization. The advantage of the topological approach is that generally optimal material distributions can be achieved.

New tools and concepts for tailoring lightweight, noise-critical structures have been created. Applications include cabins, partitions, enclosures, and lightweight panels in general. One future development is topological optimization for bandgaps. Another is to include vibro-acoustics intrinsically in optimization problem-solving.

Sound quality

The first step was to clarify the characteristics of the noise generated by the crushing of hard minerals. The characteristics include the levels, spectrum, and temporal effects. The noise from the rock-crushing stations was evaluated and analyzed on two sites, one in Vantaa and another in Kalanti. The evaluation results from the Vantaa site were presented at the Euronoise conference (Antila et al. 2015).

Annoyance from noise was studied by recording the noise on the site, and computing the psychoacoustic parameters of the recorded and synthesized noise. The recordings of the noise are especially important in assessing the psychoacoustic features of the noise by post-analysis. If only noise measurements are carried out, without the original recordings, such an analysis cannot be carried out.

The noise may be synthesized using the features of the recorded sound. Using this information, the goal was to find measures to treat the most harmful noise frequencies effectively, and to save effort on other frequencies. Furthermore, the vision is to be able to connect such know-how seamlessly with material development, hybrid materials, and structures.

Combining noise analyses and perception to develop hybrid materials and structures.

Figure 11. Lemminkäinen's asphalt plant, Lempäälä, on May 15, 2014

Figure 12. **An excursion to Lemminkäinen's asphalt plant, Lempäälä, on May 15, 2014**

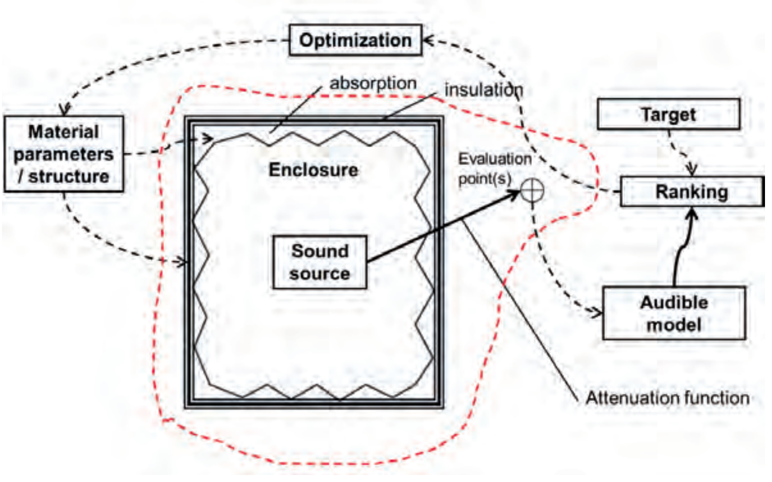


Figure 13. The virtual enclosure concept consists of a modeled structure (enclosure) with a wide parameter set for sound insulation and absorption. The noise is measured at a virtual evaluation point using the audible model, and its sound quality aspects are ranked accordingly

The virtual enclosure concept links sound insulation, absorption, and quality, as shown in Figure 12. Sound insulation and absorption characteristics of materials and structures are virtually evaluated. Key elements of the virtual enclosure concept are the enclosure insertion loss (IL) model and the audible model, which is here based on earlier work, such as in a mine loader (Antila & Kataja 2015).

The novel virtual enclosure concept enables versatile evaluation of sound insulation and absorption characteristics of materials and structures.

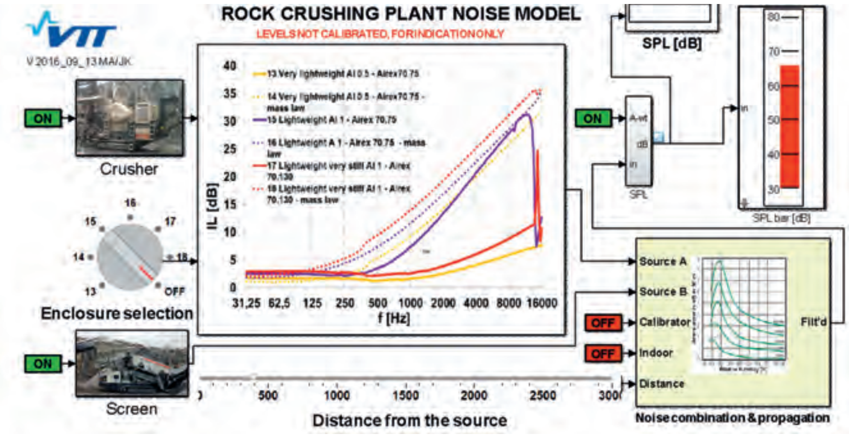


Figure 14. **A two-source audible model to evaluate the effects of various structures on the sound quality of an audible noise**

A two-source audible model was created to evaluate the effects of various structures on the sound quality, as illustrated in Figure 15. The noise sources are close-recorded sound of the crusher and the screen. The rock-crushing station in Kalanti consisted of these two components. The crusher noise was treated with frequency-dependent insertion loss (IL) virtual enclosure filters to mimic the effect of the actual enclosure. The virtual enclosures were based on the developed periodic structures. There were very lightweight and lightweight periodic structures, and also structures without periodic treatment, following only the mass law.

Further information

KEY PUBLICATIONS:

Antila, M. et al., 2015. Psychoacoustic Evaluation of Rock Crushing Plant Noise. In Proc. of Euronoise 2015.

Karhu, M., Lindroos, T. & Miettinen, A., 2015. Geometriapohjaisen ohjelmiston (GEODICT) mahdollisuudet ja soveltuvuus avosoluisen vaahtorakenteen akustisten ominaisuuksien ennustamiseen. In Akustiikkapäivät 2015. Kuopio: Akustinen seura ry, p. 7.

Tanttari, J. & Parviainen, H., 2015. Suodattavat rakenteet ja akustiset metamateriaalit. In Akustiikkapäivät 2015. Kuopio: Akustinen seura ry, p. 6.

CONTACT PERSONS:

Marko Antila, Tomi Lindroos, Jukka Tanttari/VTT
Juhamatti Heikkilä, Marke Kallio/Metso
Ari Karjalainen/Machinery Acoustics
Lasse Kinnari/NMC Cellfoam

LIGHT MULTIFUNCTIONAL HYBRID STRUCTURES

P3

Kari Dufva/MAMK
Essi Sarlin/TUT

Controlling the interfacial properties in hybrid materials

Summary of the project's motivation and achievements

Society imposes increasing requirements for energy efficiency, operational performance, durability, and safety in engineering and in various industrial sectors. New hybrid material solutions, together with advanced modeling tools, are seen as enabling technologies to meet this demand. With multicomponent materials, such as reinforced composites, sandwich structures, and multilayer materials, overall performance of structures can be improved and total costs of ownership minimized.

In all hybrid material applications, the adhesion between the constituents is the key challenge. Thus, adhesion mechanisms, methods to improve durability, and technologies to monitor the state of adhesion are studied and developed intensively. In addition, standard simulation programs typically disregard or simplify the complicated nature of adhesive joints between dissimilar materials. Thus, simulation and modeling methods also require further development.

The use of hybrid materials in challenging environments sets high requirements for the reliability of their service life estimations. Mechanical degradation and mechanisms of failure are critical issues for fiber-reinforced polymer matrix composites and other hybrid materials and, consequently, need to be well understood. The degradation depends on the individual material constituents and their interfaces, but also on other factors such as the quality of manufacturing steps. Thus, the design approach for new structures should be based on in-depth knowledge of the effects of different factors on interfacial durability.

This project concentrated on **controlling the interfacial properties** in the hybrid materials. Different material combinations, such as **adhesive metal-composite, metal-rubber, and fiber-matrix interfaces** were studied. The aim was to control and improve the chemical, mechanical, and thermal properties of hybrid materials, and to be able to predict and monitor their behavior and lifetime in operational conditions. The emphasis was on industrially sound methods that could be scaled into production.

Substantial effort was focused on the environmental resistance of the interfaces. The structures were exposed to a variety of environments and tested in different atmospheres to identify and separate the effects of individual environmental factors. Actual service environments, less found from academic research reports, were used to ensure the relevance of the research results in the industry. In addition, close collaboration between the industrial and academic partners was sustained, to ensure industrially applicable manufacturing and test methods.

Another target was to **implement damage and failure criteria for composite materials in modeling tools**. In the industry, there is a need for easy-to-use modeling tools that consider the realistic failure modes of composites, such as delamination, which is one of the most typical damage modes in composite materials. The objective was to incorporate these failure mechanisms into the modeling tools already used in the industry, and to verify the results to prove that the implemented prototype code is able to produce equivalent results.

In general, the newly developed methods and procedures improved the performance of the hybrid materials, especially in harsh environments. The methodologies were faster, simpler, and easier to scale upward and implement into industrial environments when compared with traditional ones. With more automated manufacturing methodologies, quality is easier to control and maintain, and that further improves the competitiveness of products. In the following chapter, some key results from the project are described. Figure 1 summarizes these cases.

The new methodologies are faster, simpler, and easier to scale upwards.

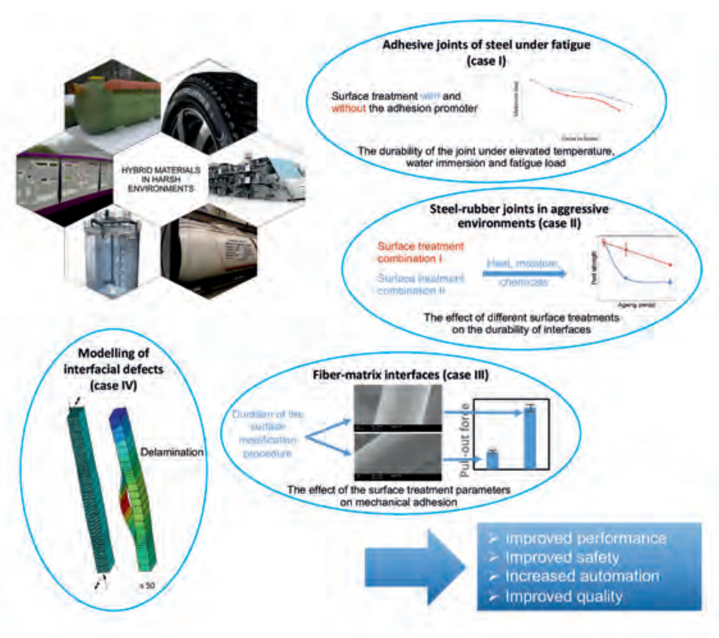


Figure 1. **Examples of the research cases in the project related to controlling the interfacial properties in hybrid materials**

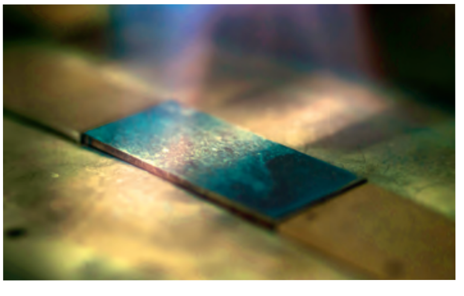
Key results and impacts

CASE I:
The surface modification of steel to improve fatigue strength of steel-composite adhesive joints

The long-term resistance of an adhesive bond depends on the type of the substrate and adhesive, and the pre-treatment of the surface. To successfully produce a reliable bonding for harsh environments, one needs to consider all the affecting factors, including the quality of manufacture. Large surface areas often cause constraints for pre-treatment processes, and some commonly used methods cannot be employed. In this work, an alternative pre-treatment method for a large roll steel surface with a composite coating was studied. As a result, the long-term durability of the interface can be significantly improved and the pre-treatment process modified in a cost-effective manner.

The pre-treatment of the surface can be optimized using an adhesion-promoting system that acts between the adhesive and the modified substrate layer. **The activity of the steel surface is increased with a nanoscale silicate layer applied using chemical vapor deposition** (Figure 2a). When applied together with a proper adhesion promoter, the silicate layer increases the environmental resistance of the adhesive joint (Figure 2b). The pre-treatment method can be automated, and it can be applied to a wide range of industrial sectors.

The pre-treatment method can be automated, and it can be applied to a wide range of industrial sectors.

a) 

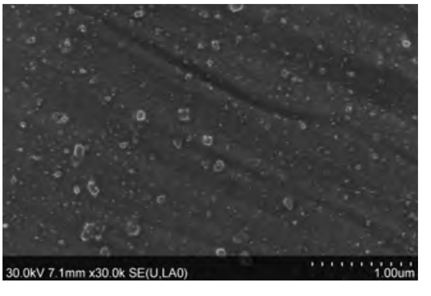
b) 

Figure 2. **a) Modification of a metal surface with the studied pre-treatment method, b) thin silicate layer on top of the surface, produced by the studied pre-treatment method**

By shortening the time used for the pre-treatment phase, the total working time required for the composite coating process can also be reduced. In applications where large surfaces are processed, the formation of cracks and voids is inevitable, and good production quality can only be ensured by precise process control and quality management. The chemical vapor deposition can be highly parameterized, which enables easy process control.

The testing procedure is based on a single lap shear (SLS) specimen, and it enables **accelerated fatigue testing of various adhesive systems in water immersion at elevated temperatures**. Using both test routines, fatigue and static, the long-term performance of a joint can be tested in a systematic and cost-effective manner. Using the testing routine, a pre-treatment method can be tailored to meet the requirements of the application, to include the optimization of material and pre-treatment process parameters for various products.

A further step, in addition to interface testing, is applying the pre-treatment method as a part of the manufacturing process. This means the modification of the processing equipment for large roll production. It also means taking some challenges of flammable gases and liquids in the surrounding environment into consideration. In the developed joining system, toxic by-products are minimized and, at the same time, material and energy savings are achieved.

CASE II:
The effect of surface treatments on the durability of steel-rubber adhesion

In hybrid materials, the use of different materials is determined by the specific requirements of a certain part of the structure. For example, certain elastomers possess a unique property combination of low stiffness and moderate strength, together with excellent chemical resistance. Therefore, they are used, for example, in the chemical industry as linings to protect metallic parts from corrosion and wear. However, the advantage of hybrids is achieved only if the components are well adhered to each other, and the interfaces maintain their properties throughout the service life of the product.

The joining of metal and rubber is achieved by an approach that combines different surface treatments of metal with adhesion-promoting chemicals and adhesives. In the operation environment, the diffusion of hot moisture and other chemicals through the rubber lining into the interface may cause premature failure of the rubber lining. An effective design approach of the rubber linings requires detailed knowledge of the individual and combined effects of different interfacial pre-treatments, as well as of adequate test methods.

In this study, combinations of different surface treatments, namely sand blasting and two different silane treatments, were used prior to the adhesive treatment on stainless steel inserts. Subsequently, bromobutyl rubber (BIIR) was vulcanized on both sides of the steel, and the samples were subjected to water immersion at 95°C. The test specimen design was similar to the actual design. Previously, it was shown that pure water, instead of the water-acid solution of the actual service environment, results in conservative test results. Thus, water was used in the tests.

During the 12-week exposure, the peel strength of the steel rubber interface decreased by 40–95% from the original value of 11 N/mm, depending on the surface treatment combination. Initially, the fracture location was inside the rubber (cohesive fracture), indicating sufficient interfacial quality. As the peel strength decreased, there was a strong correlation between it and the fracture location (fraction of cohesive fracture). Although a cost-effective manufacturing method that would be simple and straightforward was originally targeted, the best results were achieved by a combination of three different pre-treatment steps. However, the silane treatment that led to the best results is easy to implement in an industrial process, and is applicable for complex substrate shapes, being thus a feasible option to improve steel-rubber adhesion in practice.

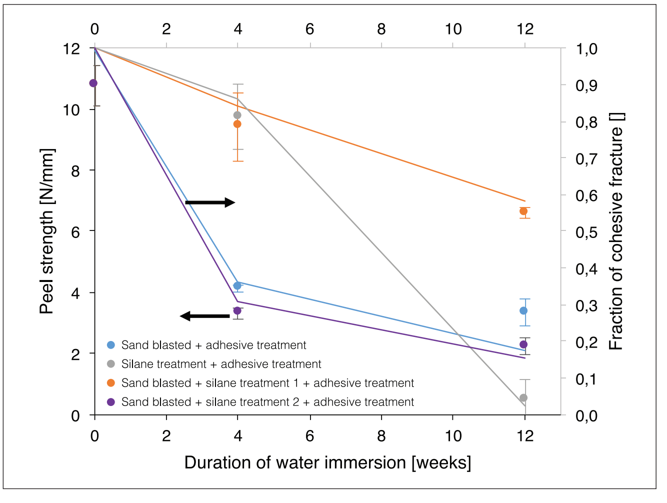


Figure 3. The peel strength (dots) and the fracture location (lines) for super duplex stainless steel – rubber interfaces subjected to water immersion at 95°C

Company impact

"The results of the research will be utilized directly in the design and selection of steel-rubber components. The results help to optimize the manufacturing process, to improve the quality of the steel-rubber components, and to prolong their lifetime. The results of this project enable us to select competitive hybrid solutions and to increase the reliability of our products."

__Mari Lindgren__, development manager, Outotec

CASE III:
A new approach to aramid fiber surface modification

Aramid fibers are high-performance materials with excellent thermal and mechanical properties. These synthetic fibers were first developed in the early 1960s and have established themselves as the ultimate material in fiber-reinforced composites for demanding applications, such as hoses, tires, and bulletproof vests. However, the aramid fiber surface is very smooth and chemically inert, making it very difficult to achieve good adhesion between the fibers and matrix material. This hinders the utilization of the full potential of aramid fibers in composites.

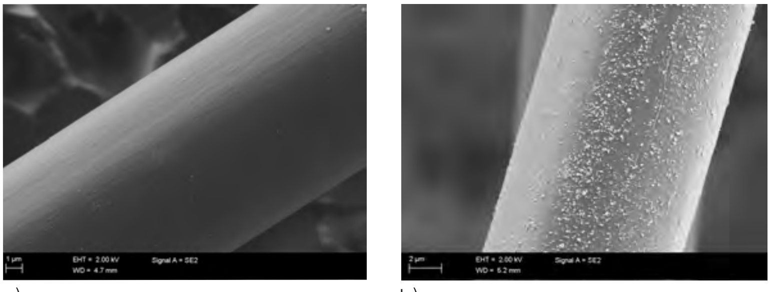
Tightening environmental regulations and the specific shortcomings of the traditional aramid surface treatments encourage the development of novel methods for the composite and fiber manufacturing industry. Recently, some new methods have been introduced, offering significant advantages over the more traditional chemical and plasma treatments, such as zero negative impact on the mechanical properties of the fibers, suitability for a broader range of matrix materials, and improved storage life. However, all of these novel methods include several elaborate process steps, which can be very difficult to scale up to meet the demands of industrial production.

Mechanical interlocking through nanoparticles produced on aramid fibers led to strong interfacial adhesion.

With the used method, aramid fibers can be tailored to suit a broad variety of composite products.

To combat these problems, this study presents a novel approach to modifying aramid fiber surfaces for improved fiber-matrix adhesion. The method **creates nanoparticles on the aramid fiber surface via microwave irradiation** (Figure 4). These particles enable mechanical interlocking between the fibers and the matrix, creating a strong interfacial bond. By increasing the amount of nanoparticles on the fiber surface, the adhesion between the fibers and matrix also increased. In this way, fiber material can be tailored to suit a broad variety of composite products. Most of the traditional adhesion-promotion methods are based on improving the chemical adhesion and are thus matrix specific.

With this surface treatment method, the adhesion between aramid fiber bundles and a rubber matrix increased by ~260% when compared to untreated aramid fibers (Figure 5). The improvement correlated with treatment duration and an additional treatment step (pre-wash), which means that the outcome of the process can be controlled by controlling the irradiation time, which directly influences the growth of nanoparticles. In addition, the best results were achieved with pre-washed fibers from which the manufacturing-related surface sizing had been removed. From an industrial manufacturing point of view, this is trouble-free because the microwave treatment could be placed right after the coagulation bath, before any surface sizing is added to the fiber surface. Tensile testing of the fibers revealed that the method has no negative impact on the tensile properties of the fibers.



a) b)

Figure 4. Scanning electron microscopy images of: a) untreated aramid fiber, and b) microwave surface-treated aramid fiber

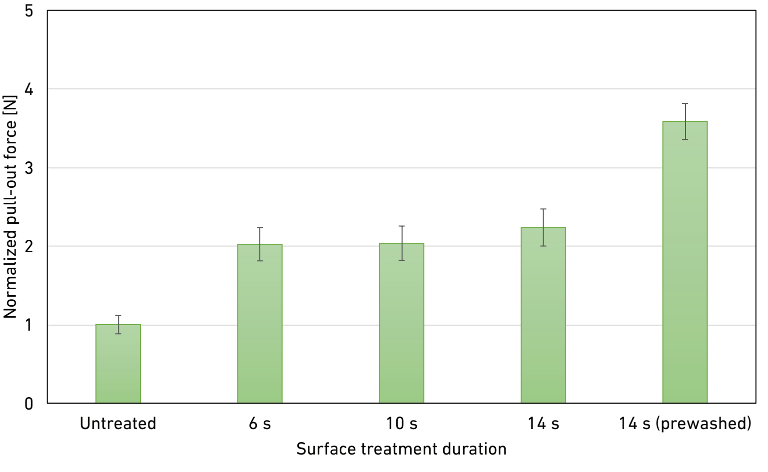


Figure 5. Bundle pull-out test results of aramid fiber in rubber, as a function of the surface treatment duration [Palola et al. 2016]

Microwave-assisted aramid surface modification – environmentally friendly, scalable, and effective.

Although the developed method was demonstrated only on a laboratory scale, it is a good basis for up-scaling and for industrial implementation. The benefit of using microwaves is that this transfers energy rapidly throughout the whole bulk of the material, enabling faster turnaround times and less wasted energy. Thus, the method is simple and rapid. In addition, microwaves are already utilized in industrial processes, for example, in curing epoxy composites and in surface activation of glass fibers, and industrial-scale equipment is already available. The use of harmful chemicals in the current method is also limited, and the chemicals used in it are less toxic and more easily handled, as they are used in powder form. Overall, this new approach to surface treating aramid fibers offers new perspectives toward efficient and improved composite manufacturing.

CASE IV:
Delamination analysis in layered composite structures

Layered composite structures exhibit various failure mechanisms, namely fiber failure, matrix cracking, buckling, and delamination, which is a separation between the internal layers of a composite laminate, caused by high through-the-thickness stresses, impacts, or manufacturing defects. Delamination may considerably reduce the load-carrying capability of a component, and may lead to significant structural damage, particularly when loaded in compression.

Simulation of delamination requires great expertise and dedicated knowledge of particular FEA programs.

Simulation of delamination requires great expertise and dedicated knowledge of particular finite element analysis (FEA) programs. The use of layered composite structures is increasing in all industrial sectors, and there is a clear need for easy-to-use fast delamination assessment tools for the detailed design phase and design validation.

Componeering Inc. studied the various aspects of delamination simulation, with the ultimate goal being to implement a delamination module into the ESAComp software, which is a toolbox for composite design and analysis. A fracture mechanics-based approach called Virtual Crack Closure Technique (VCCT) was the choice for further evaluation. ESAComp is strong in the shell-based simulation of layered structures and supports a geometrically nonlinear analysis approach. A solid theory exists to determine the strain energy release rates (SERR) at the crack tip of the model, idealized with shell elements. SERR is a measure to quantify whether conditions for crack growth are met. An additional theory based on the crack tip element (CTE) complements the approach when determining the SERR values related to the different delamination modes. A proof of concept code was prepared, and the function was verified against a set of various laminate and load configurations.

The gained knowledge related to the delamination analysis was successfully utilized in the damage tolerance analysis of the Anisogrid payload adapter, which is a very recent development project promoted by the European Space Agency (ESA/ESTEC). The prime contractor of the project was Airbus Defense and Space. The Anisogrid payload adapter (Figure 6) is a conical carbon fiber-reinforced lattice structure that is manufactured using automatic fiber-placement technology. The adapter is placed between a satellite and the VEGA launcher.

The developed method was successfully utilized for a European Space Agency case study.

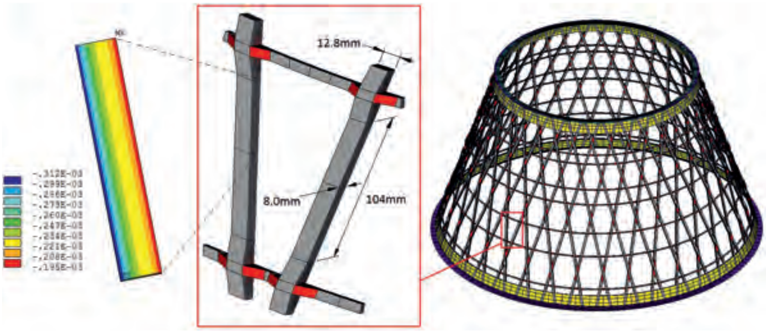


Figure 6. Global solid model (right), a detailed view of the model (middle), and the longitudinal strain [abs] distribution (left) at the specific location

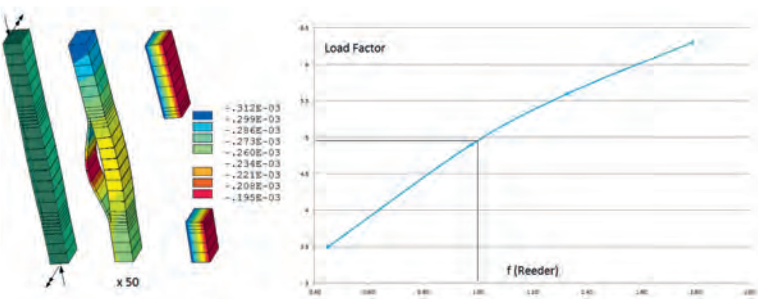


Figure 7. Idealization of the local shell model, including the definition of the delamination (left). The illustration shows thickness in real scale. Deformation of the model is scaled by a factor of 50 when loaded with the design load (second image from left). Strain distribution [abs] of the intact zones (second image from right). The relation between the load factor and the value of Reeder's delamination criterion f (right). A delamination criterion value of 1 indicates the onset of delamination. The value one of the load factor is related to the design load

A global parametric FE model based on solid elements was created to simulate and optimize the structure. Strain levels were extracted from certain points of the intact structure (Figure 6). A local shell model, including the definition of the idealized delamination, was created. The loading and boundary conditions were set in such a way that the strain distribution in the intact region corresponded to the global model (Figure 7). The SERR at the crack tip was determined using the different crack depths. Furthermore, SERR values related to the different delamination modes were defined. This information, together with the material-related fracture toughness parameters, was used in Reeder's delamination propagation criterion. The critical value of the criterion would indicate the onset of delamination. The relation between the load factor and the value of Reeder's delamination criterion f is shown in Figure 7. The study indicated that the structure is tolerant with respect to delamination. Potential defects at the layer interfaces do not lead to catastrophic failure of the assembly.

Further information

KEY PUBLICATIONS:

Sarlin, E., Rosling, A., Mustakangas, M., Laihonen, P., Lindgren, M. & Vuorinen, J. 2015, Diffusion of acidic solution through rubber at high temperature and its effect on metal-rubber interface degradation, SAMPE Europe Conference, Amiens, France, 14th–18th September 2015.

Palola, S., Sarlin, E., Kolahgar Azari, S., Koutsos, V. & Vuorinen J. 2017, Microwave induced hierarchical nanostructures on aramid fibers and their influence on adhesion properties in rubber matrix. Submitted to Applied Surface Science.

Mangas, C. B., Vilanova, J., Díaz, V., Samartín, C. R., Kiryenko, S., Katajisto, H., Pérez-Álvarez, J. 2016, Anisogrid payload adaptor structure for VEGA launcher, European Conference on Spacecraft Structures, Materials and Environmental Testing (ECSSMET), Toulouse, France, 27th–30th September 2016.

Antti Ahvenainen: 3D Solid Modeling for Composite Pressure Vessels. Master's Thesis. Aalto University, 2017.

Juho Posio: Interlaminar shear strength testing of non-unidirectionally reinforced composites. Master's Thesis. Aalto University, 2016.

CONTACT PERSONS:

Kari Dufva/Mikkeli University of Applied Sciences,
kari.dufva@mamk.fi (case I)

Essi Sarlin/Tampere University of Technology,
essi.sarlin@tut.fi (case II and III)

Harri Katajisto/Componeering,
harri.katajisto@componeering.com (case IV)

PARTICIPANTS:

Componeering, Ekin Muovi, Kevra, Muovityö Hiltunen, Nokian Tyres, Outotec, Teknikum, Valmet, Wavin Labko, Aalto University, Mikkeli University of Applied Science, Mikpolis, Tampere University of Technology, Åbo Akademi

Nani Pajunen (Sitra), Riikka Mäkikoskela, Olli Dahl/Aalto University
Pasi Turpeenniemi, Petteri Lautso/Ruukki Construction Oy

Transition towards Circular Economy – life cycle perspective in material development

Aiming the circular economy and saving natural resources

The current state of environment has been achieved by acting linearly. At the same time, we know that transition towards circular economy cannot be made the same way that we have used to, trusting only a market economy and economic growth. Environmental improvements have been promoted, some progress has been made, but major steps towards sustainability have not been taken. Industry is now facing significant change, from process related environmental thinking to product-based environmental thinking.

Engineers make decisions which have lifelong influence and even longer on environment and society. Material engineers in case of saving natural resources and increasing material cycle, have an important role to play in the transition towards sustainability and circular economy. The best knowledge of minerals and materials is in the material development phase. If we want to increase the cycle of different materials, it is vital to make decisions towards circular economy in early phase of product's life cycle.

One of the driving forces, for making new composite and hybrid materials, is to lighten a product and reinforce it. With lightening the target is to save energy in use phase, e.g. in transportation. Much of the development of new devices is driven not only by the drive to fulfill the consumer needs but also of lower productions costs by easier mass production methods like joining by gluing (instead, say, nuts and bolts joints) and many others.

At present almost all products in use are composed of a variety of material combinations. The end of life phase of such complex products becomes non-homogenous. Scrap may contain valuable resources that can be recovered and reused but also parts that do not have economical recycling means. It is vital to take recycling perspective into account already both in composite and hybrid material development and in design phase of the product, to achieve a balanced approach between the different aspects of sustainability.

The pressure to act more sustainable way and to produce environmental information is increasing. Also customers are asking environmental impacts of the products and production. Those companies that choose to be forerunner in environmental responsibility may have advantage over their competitors. The decision will benefit themselves, their customers and naturally environment.

Aiming the circular economy and saving natural resources, the objectives of this research project were; to include life cycle thinking and recyclability of hybrid and composite materials in material development and product design phase; to include life cycle thinking to operational, management and strategy level of decision-making; to include all actors of the supply chain in development work towards material efficiency; to describe the complexity of the recycling in industrial system from material development, via product design and use phase to end of life; and to increase use of industrial residues in products.

In this study, we had a new kind of cooperation, when targeting the real change in development and design processes. We combined two disciplines, engineering science and fine arts. We brought the cyclic artistic thinking into engineering science and environmental research. The new research combination makes the existing information visible in a new way, and it will change attitudes and ways to act by means other than traditional linear rationality.

The current state of the environment has been achieved by acting rationally and linearly. Also environmental improvements have been promoted in the same way. Some progress has been made but major steps towards sustainability have not been taken. The traditional, rational and linear thinking has not worked in order to achieve significant sustainable development. Just as major obstacles are the silos, the social structure, in which each sector operates separately and intersectoral collaboration is limited. Therefore, in this project, we promoted circular economy via breaking out of the old ways of thinking, breaking out the silos and tackling the barriers.

Positive attention to circular economy

In this research, we were looking primarily at ways of transforming practices, so our research was realized in workshops and interviews. We invited actors from multiple sectors of society: from industry, the commercial sector, public authorities, scientific community and art world as well as individual consumers to participate in. By bringing together people from different fields, we gave birth to a new, that a certain, homogeneous expert community or group would not have been able to assume.

Our aim in this project was to attract a lot of positive attention to the challenge of circular economy and finally to create something new from chosen product with an idea of thinking in a new way and upcycling. Innovative solutions for sustainability and circular economy were sought specifically with the methods of artistic thinking and artistic research. We studied how the material, spatial and cyclic thinking can be combined with linear thinking.

Upcycling the sandwich panel – from ideas to concepts, demos.

The chosen product of the case study, sandwich panel, consists of an inner insulation core between two steel sheet layers. The insulating core can be mineral wool or polyisocyanurate. Sandwich panels are typically used in facades, partition walls and ceilings.

Figure 1. **Sandwich panel with steel**

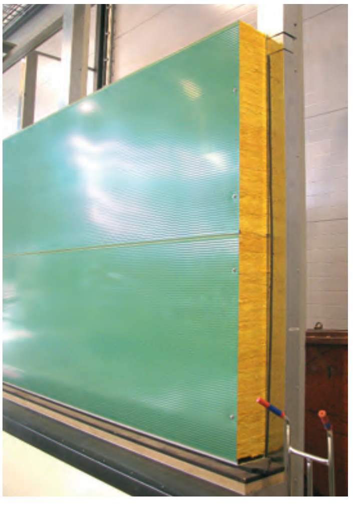


Figure 2. **Product during installation**

Our collaborative company, Ruukki Construction Oy, produces sandwich panels of recycled steel and insulation. A subcontractor produces insulation of used glass for Ruukki. Ruukki Construction sees sustainable use of materials as a key competitive factor: Company's target is to minimize waste production and increase utilization of the used sandwich panels.

In the first workshop, the target was to find challenges in recycling of the chosen case-product, sandwich panel. The production and product development experts of Ruukki Construction Oy and all its subcontractors for the sandwich panel took part in the first workshop. Challenges in end of life (EoL) phase were listed by all the subcontractors of the product.

For the second workshop people from various fields were invited, for example, designers, technical designers, sales professionals, consultants, architects, city planners, material experts, builders, contractors, visual artists and research scholars. In the workshop, we studied the entire life cycle of sandwich panels and tried together to find the wider use for the product processed of recycled material and the new uses for the once used sandwich panels.

The first brainstorming session yielded ideas how the sandwich panel could enable new products and services in addition to the current product and how to upcycle it. The basic idea was to rethink the whole production process and the final product. What do we need in the future and why? What will happen to the sandwich panel in its end of the life phase? Is it possible to reuse those for new purposes?

The first individual brainstorming resulted in many ideas, which were of the same types. We brought together the similar ideas generated from several expertise perspectives, discussed, examined and developed them further with this multi-disciplinary group of experts. We worked on large papers, which were hung on the wall or laid on the floor. This allowed working in motion. New concepts for the current sandwich panel, new products, services and entire modules were developed together in the short time frame. We managed to develop specifically entities and packages, which are important for sustainability and circular economy.

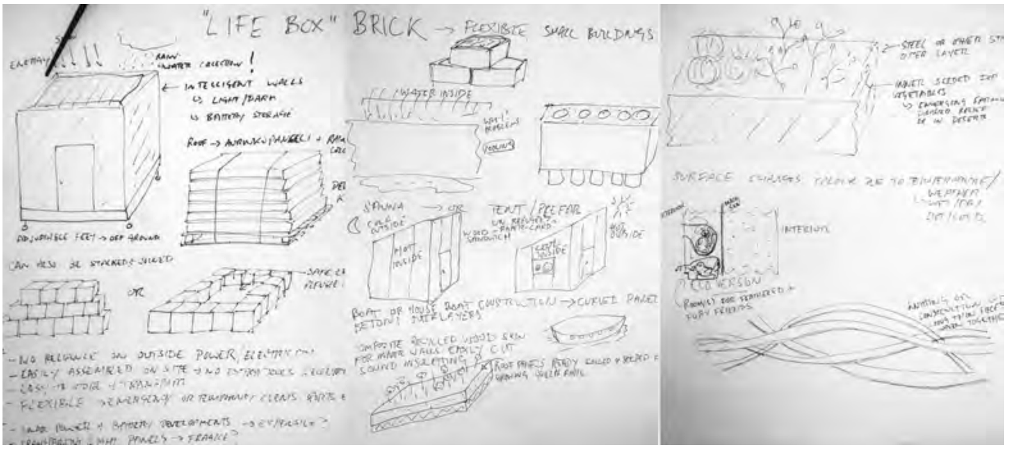


Figure 3. **Brainstorming and ideation on paper – new concepts for upcycling the sandwich panel**

The objective of the third workshop was to seek new uses for the product processed of recycled material. The theme was upcycling with an artistic approach. Instead of brainstorming and ideation, the participants worked this time on sandwich panels by hand with the aim to make works of art and design. The participants were partly the same people as in the second workshop, but now we expected that the multi-disciplinary group of participants had the experience or willingness of artistic, design or handicraft work and manual labor. We, as researchers, aspired to follow the artistic thinking of workshop participants.

Figure 4. **Hands-on method I**

Figure 5. **Hands-on method II**

In the third workshop, we aimed at finding innovative solutions for the upcycling of the chosen industrial product. Some of the ideas came up in the second as well as in the third workshop, but this time we carried out the designs concretely. This resulted, for example, as the uniquely painted wall panel, the fireplace element embedded in the wall and the birdhouse built of once used sandwich panel.

Figure 6. **Some outcomes of the third workshop**

Transition needs cooperation between silos

The research project started with an idea how to integrate life-cycle thinking in material development work and product design. At the same time, the results of a doctoral thesis (Pajunen 2015) showed that transition towards circular economy needs cooperation between different sectors of society. However, the existing silos make the situation difficult. In addition to this, the recent artistic research (Mäkikoskela 2015) defined that artistic thinking is based on the sensory experiential and thus proceeds rather cyclical than linear. Due to the above-mentioned considerations, we decided to break out of our own siloes and to combine two distinct disciplines. We hypothesized that with this combination we could produce an innovative perspective to promote some steps in circular economy.

Transition towards circular economy needs cooperation between different sectors of society – breaking silos needed.

As a conclusion, once again, engineers have an important role to play in the transition towards sustainability: the decisions they make have a lifelong influence and even longer on environment and society. At the same time, we know that transition towards circular economy cannot be made the same linear way that we have used to, trusting only a market economy and economic growth.

What did we learn?

Upcycling approach and the hands-on method brought new dimensions to the whole project. Working by hand was activating also brain in a new way. We designed, made, saw and experienced the upcycled product concretely. We became convinced that the focus areas of the research project, material development and industrial product design, are very suitable for this kind of approach. And especially, research work, do not matter the field of research, is always creative practice.

Engineering is an art

International academic interest in circular economy is growing. In the XXVIII International Mineral Processing Congress (http://www.impc2016.org), on September 2016, in Québec City, Canada we had an opportunity to give a keynote presentation with a theme: "Breaking out the silos – towards sustainable society – art, engineering and decision making perspectives". During the presentation the audience was asked to answer a few questions. One of the questions was: "Art, engineering and decision making – what an earth or of course?" And the answer of the one of those present was: "Of course – engineering is an art".

Art Exhibition

Art exhibition was arranged based on the results of the third workshop, at Media Centre Lume's Gallery April 3–12, 2017 (Aalto Arts, Hämeentie 135 C, Helsinki).

Company impact

"We are undergoing a major change in how fast the world is transforming. Traditionally our built environment has been developed assuming that the processes it facilitates will not change. This contradiction will have to be resolved one way or another. One way to look at it is to change the perspective so as to start the loop from another place. Studying our building materials as future raw material through truly multidiscipline approach showed promising possibilities."

***Petteri Lautso,** customer value director, Ruukki Construction Oy*

Further information

KEY PUBLICATIONS:

Leading the cycle – Finnish road map to a circular economy 2016–2025. Sitra Studies 121. <http://www.sitra.fi/sites/default/files/sitra_leading_the_cycle_report.pdf> Accessed 30.11.2016.

Mäkikoskela, R. 2015. Ympäri, sisällä. Kolmiulotteinen työskenteleminen kuvataiteessa [Inside and Around: Three-dimensional Practice in Visual Art]. Helsinki, Finland: Aalto Arts Books. Aalto University Publications, Doctoral Dissertations 143/2015.

Ojanen, S. 2016. The potential and limitations of re-using and recycling of construction products from the perspective of circular economy. Master's Thesis, Aalto University. <https://aaltodoc.aalto.fi/bitstream/handle/123456789/22169/master_Ojanen_Severi_2016.pdf?sequence=1> Accessed 30.11.2016.

Pajunen, N. 2015. Decision making towards sustainability in process industry – drivers, barriers and business opportunities. Doctoral dissertation. Aalto University. 978-952-60-6360-7 (electronic).

Pajunen, N., Rintala, L., Aromaa, J., Heiskanen, K. 2015. Recycling – the importance of understanding a complexity of the issue. International Journal of Sustainable Engineering. Online 25 August 2015. DOI:10.1080/19397038.2015.1069416.

CONTACT PERSONS:

Nani Pajunen, Sitra (Aalto University),
nani.pajunen@sitra.fi, nani.pajunen@aalto.fi

Riikka Mäkikoskela/Aalto University,
riikka.makikoskela@aalto.fi

Olli Dahl/Aalto University,
olli.dahl@aalto.fi

Pasi Turpeenniemi/Ruukki Construction Oy,
pasi.turpeenniemi@ruukki.com

Petteri Lautso/Ruukki Construction Oy,
petteri.lautso@ruukki.com

PARTICIPANTS:

Aalto University, Ruukki Construction Oy, Teknikum Oy, Kevra Oy, Muovityö Hiltunen Oy

POLYMER MULTIFUNCTIONAL SLIDING MATERIALS

P4
SP1

Helena Ronkainen, Anssi Laukkanen/VTT
Olli Orell, Jyrki Vuorinen/Tampere University of Technology
Heikki Kettunen/Valmet Technologies Oy

High performance for industrial components through polymer materials in oil-free contacts

Summary of the project's motivation and achievements

The industrial need and scientific challenge is to develop polymer-based materials that can produce low wear with controlled static and dynamic friction in demanding conditions with a long life-time. The materials should have sufficient heat resistance, good impact resistance, and superior wear resistance. Generating a theoretical and research-based background of tribology mechanisms in sliding conditions, micro-slipping, and filtration tasks is an important part of the development.

A large set of polymeric materials with various compounding has been evaluated in laboratory wear testing to evaluate optimized sliding materials with controlled friction. Broad background information on material options and modifications has been generated. In addition, testing methods have been developed further, to better evaluate the different results obtained.

To understand micro-slide in rolling contact, and the corresponding wear mechanisms of rolling surfaces, both novel experimental material characterization methods and computational modeling methods were developed and used. Having all these together, it is possible to generate broad understanding of the application conditions, especially for multi-component composite materials, which is otherwise not possible. Furthermore, fundamental – not just mental – knowledge is needed to compete against global actors in the same application areas.

Research on filtration contact started with theoretical evaluations of potential modifications of filtration materials, methods of modification, and potential effects on filtration processes. Further work continued as experimental research to find potential options for the filtration process. From a set of materials, some were found to be very promising and were initially tested from the filtration process point of view.

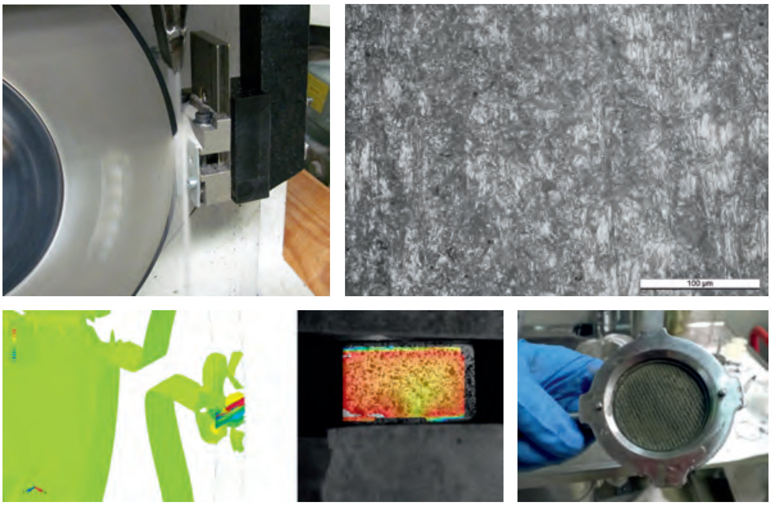


Figure 1. Characteristic photos from experimental testing and modeling of the OfCo sub-project

Unique state-of-art experiments on materials and application

The solution to any mechanical problem in question, in this case a rolling contact, requires knowledge of relevant material properties. As such, proper determination of all the elastic properties of materials is a challenge for experimental research. Typically, the Poisson ratio and shear modulus are guesstimates, as well as isotropy along the coordinate system and in the loading direction of materials. The challenge becomes even more difficult when composite materials with a largely heterogeneous microstructure are under study. A large uncertainty arises in comparing various material samples and estimating those in application.

At Tampere University of Technology, a rich set of experimental methods were developed to measure a full matrix of elastic properties of material samples. VTT assisted with micro- and nano-indentation tests. Not only macroscopic properties are measured, but also local micro-scale properties with distributions. In the project, several different composite samples, one polyurethane sample, and one rubber sample were tested. Evidently, the results do not even to a small degree fully cover all rolling materials of interest, but give a basic view of the range of properties. Naturally, the developed methods are then available for future studies outside the project.

During the project, it was necessary to develop specific methods for the preparation of a high-precision specimen from composite materials for compression testing. At macroscopic level, test pieces from rolling contact have a curvature shape, but compression tests require planar structures. This was solved with a special flat-winding arrangement for sample fabrication. Second, cutting a small test piece with exactly parallel compression surfaces required special grinding apparatus.

Measurement of shear modulus also requires specific high-precision testing geometry to generate controllable shear stress in the specimen to be measured. A further sampling set-up was developed for fabric characterization (burn-out) and for single-fiber tension testing (outside Hybrids). Topography imaging was based on silicone replicas, as another type of sampling would mean destroying the objects of interest.

Compression and shear testing are combined with digital image correlation (DIC), which gives full-field results showing the local strain distribution of the test specimen under loading. Figure 2 shows examples of local values of strain and Poisson ratios, plus the corresponding macroscopic graphs.

An important direct outcome from the studies is reliable representative values for contraction and shear modulus, together with compression modulus. A comparison of these shows that orthotropic material models give reasonably good material estimation (Figure 3), which was not self-evident at all. This result makes further testing and material modeling simpler in the future, when we can assume orthotropic models are applicable.

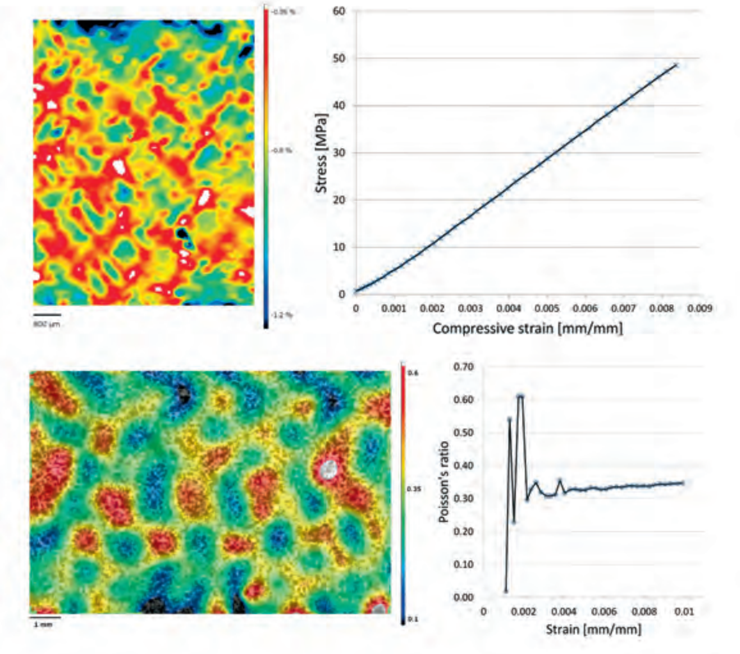


Figure 2. Top: full-field strain map showing compressive strain ε2, P = 40 MPa, and the corresponding stress-strain curve. Below: full-field map showing Poisson's ratio ν32, P = 40 MPa, and the corresponding macroscopic contraction against macroscopic strain

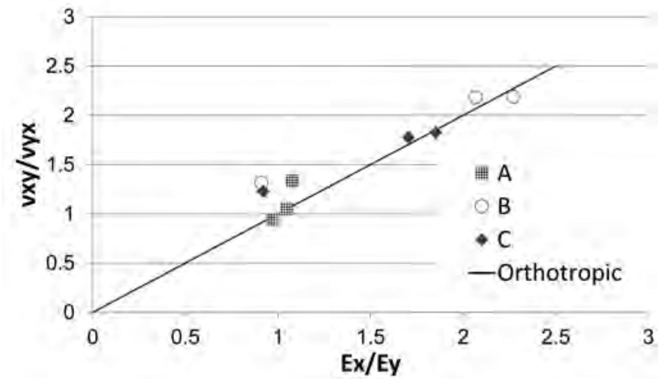


Figure 3. Evaluation of the orthotropic behavior of the materials (x, y = from 1 to 3)

As a final phase of research, the usability of composite material models found in the literature, between micro scale and macro scale, are evaluated. The benefit of such models is obvious in designing a target material from its components.

In the project, real roller-wearing surfaces were studied, based on micro-scale resolution topography images from replica samples. A whole new level of imaging was introduced, and the same results are not achieved with traditional SEM imaging. Figure 4 shows an example of worn-out cover topography. Topographical imaging provided important evidence that confirmed the mechanism of the vibration-based wearing process, which has not previously been known.

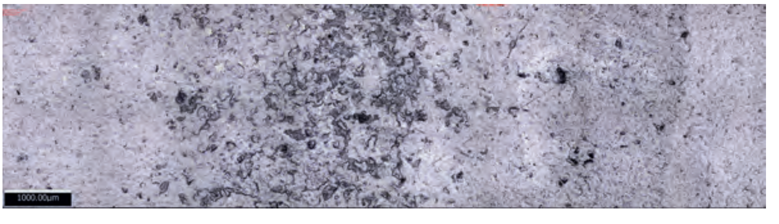


Figure 4. Topography image of worn-out roller surface

Computational modeling of rolling contact

VTT has deep knowledge of computational modeling of various applications with different scales of observation. Figure 5 shows the schematics of how roller contact was modeled: first, starting from the geometry of the system and external boundary conditions; then including material properties as macroscopic values based on experimental results received in the other part of the project; then increasing the complexity of the model by adding a micro-structure measured as a topography variation. The final step would be to add a full microstructure of composite materials to the models, but that remains future research work.

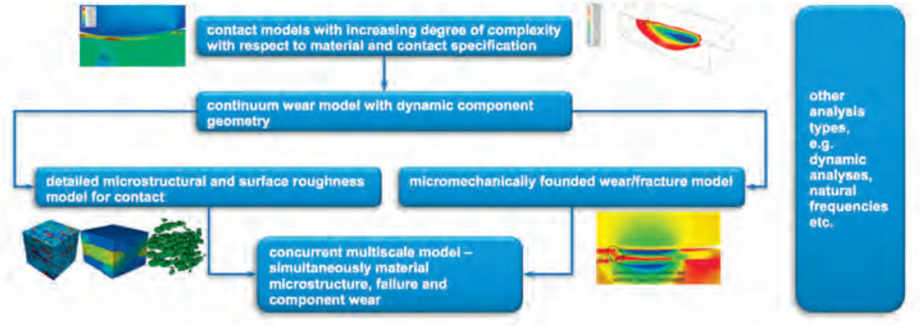


Figure 5. Incremental modeling approach for wear in rolling contact

The main pragmatic benefit of modeling is that it enables expansion of the scope of predictions much beyond the possible experimental range. Once the basic set-up (Figure 6) is done, it is very easy and fast to evaluate different scenarios for the system. The basic model was used to evaluate parameters such as static versus rotation condition, loading force, material parameters from the experimental part of project, contact friction, slip, and macroscopic surface defects.

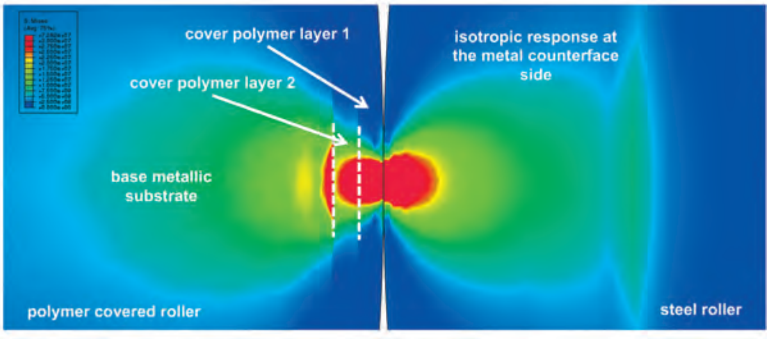


Figure 6. Model-generated layout with a von Mises stress field plotted under "reference" contact conditions

Figure 7 shows the effect of friction and slip on contact shear. Most critical conditions occur with a slipping condition with high contact friction. With macroscopic defects in the model (Figure 8), and also with the micro-scale topography included from experimental measurement, the main indication is that defects generate growth of defects by nature. This agrees with a common impression from real-life cases, which is that initial defects tend to enlarge.

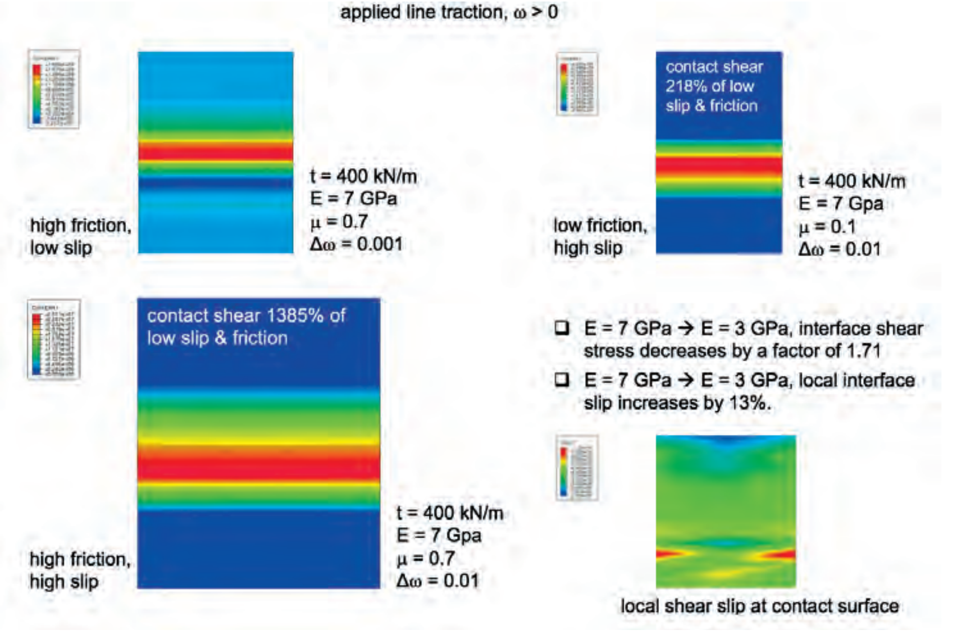


Figure 7. **Comparison of slip cases in a macroscopic model**

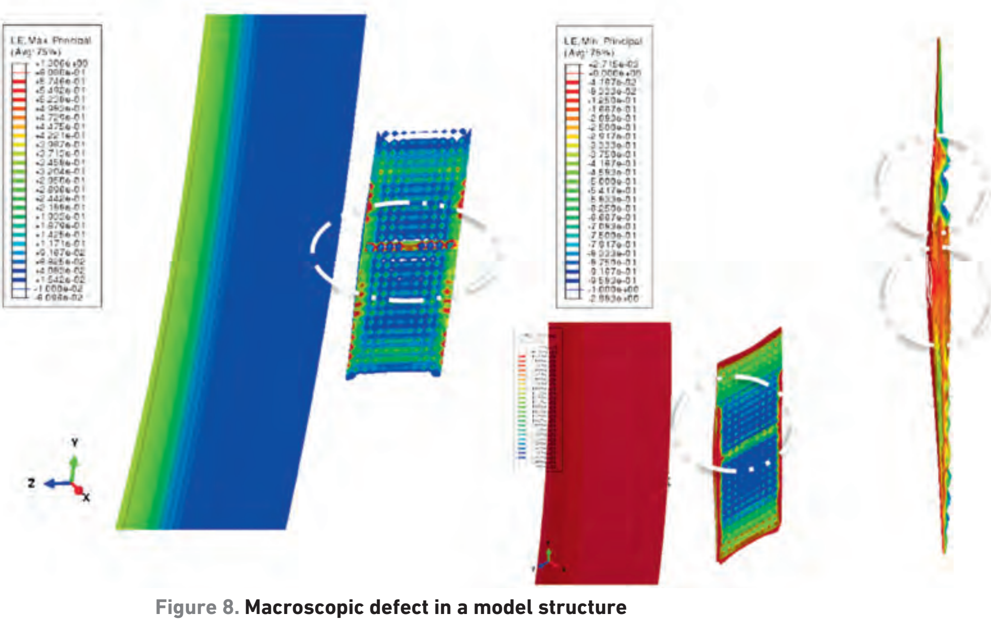


Figure 8. **Macroscopic defect in a model structure**

Company impact

"Projects like DIMECC Hybrid Materials bring together top know-how on a national level to solve future challenges. Once again, the results of the project have the potential to boost the competitiveness of both industry and academia. Understanding the interaction between materials in various applications is vital for developing industry-leading products and for world-class research."

***Teemu Soini**, development engineer, Nokian Tyres plc*

"An important aspect of the results is verification of various theoretical material models presented in the literature. This makes further development of roller contact applications more reliable and easier. Having an understanding of micro-level variability of local stress and strain conditions is also an important aspect when considering development on composite materials. In the end, performance comes out of micro-scale details."

***Heikki Kettunen**, director, R&D, Valmet Technologies Oy*

Further information

KEY PUBLICATIONS:

Orell, O., Vuorinen, J., Jokinen, J, Kettunen, H., Hytönen, P., Turunen, J. & Kanerva, M., Characterization of elastic constants of anisotropic composites in compression using digital image correlation, (submitted to Composite Structures)*

Mechanical characterization of laminates with micromechanical and numerical analysis comparison TUT & VTT (to be submitted)*

Article 3 Rolling contact model including micro topography, VTT & TUT (to be submitted) *

Article 4 Abrasive wear testing of polymeric materials, VTT

CONTACT PERSONS:

Helena Ronkainen, Anssi Laukkanen/VTT
Olli Orell, Jyrki Vuorinen/Tampere University of Technology
Heikki Kettunen/Valmet Technologies Oy

PARTICIPANTS IN SP1:

VTT, Tampere University of Technology, Valmet Technologies Oy, Nokian Tyres Oy, Carbodeon Oy

*All with Valmet Technologies

POLYMER MULTIFUNCTIONAL
SLIDING MATERIALS

P4
SP2

Marke Kallio/Metso Minerals
Arto Lehtovaara/Tampere University of Technology

Lubricated hybrid sliding bearings for demanding operational conditions

Summary of the project's motivation and achievements

Motivation

Sliding bearings are widely used in heavy industry, such as in mineral-crushing machines, combustion engines, generators, (steam) turbines, and marine applications. Competition in the world-wide market drives these products toward higher power density, longer lifetimes, higher reliability, lower power loss, and reasonable cost. The critical components, which are hindering this development, are sliding bearings, where the design and properties of sliding contact are the key factors.

The goal of the sub-project was to improve sliding bearing performance in heavy operating conditions by using advanced polymer liners, multilayer bearing structures, and bearing designs. The main target was to enable heavy power density and shaft misalignment without smearing and seizure of the bearing. The overall goal was to **improve the energy efficiency of the crushing process and diesel engine**. The scientific goal was a) to model and simulate sliding bearing performance and damage risk in hydrodynamic lubrication conditions in heavy operating conditions, b) to evaluate and improve friction, wear, and smearing performance and to determine surface failure mechanisms using lab-scale bearing tests, and c) to develop polymer liner properties and adherence to the bearing surface. The project was divided into three **main tasks:**

1. Polymeric multifunctional sliding materials
2. Experimental evaluation of multilayer bearing performance and damage risk
3. Modeling of hybrid sliding bearing performance

The main achievements can be stated as follows:
In task 1, the potential material candidate for polymer liner was found to be high-performance polymer, polyamide-imide (PAI), with different fillers such as milled carbon fiber, polytetrafluoroethylene (PTFE), and

carbon nanotubes. Uniform films with a thickness ranging from 20μm to150μm were fabricated on the top of a lab-scale thrust bearing. The fabrication technique enabling detailed tailoring with different fillers was proven to be feasible, and the first test with a proto bearing was promising and showed good adherence to the bearing surface.

In task 2, bearing performance in terms of the friction, wear, smearing, and load-carrying capacity of the variety of bimetal, multilayer and bulk polymer bearings were evaluated with lab-scale bearing test rigs. EU-level restrictions on the use of lead have created an increasing demand for lead-free or low-lead bearing materials. The lead-free bismuth bronze bimetal bearing showed load capacity of the same level as the reference bearing made of continuously cast leaded tin bronze CuSn10Pb10, and it was concluded to have the potential to substitute for the leaded tin bronzes in the studied heavy operating conditions.

In task 3, a parameterized calculation model for hydrodynamic journal bearings was successfully developed, which takes into account hybrid (multilayer) materials and bearing design concepts, shaft misalignment, and elastic and simplified thermal deformations of the bearing surfaces and housings. It is found that deformations have a significant effect on bearing performance, and that the deformation behavior can be altered using polymer hybrid bearings. It was shown that the polymer layer effectively eliminates high edge pressures on misaligned bearings, and has a beneficial increase in film thickness in the area of maximum pressure. The design of these hybrid bearings is delicate and their properties must be tailored according to the operating conditions in order to obtain full performance benefits.

Key results and impacts

Polymeric multifunctional sliding materials

Hybrid bearings, consisting of functional polymer layers on metal substrates, can offer advantageous property combinations over more conventional metal bearings. Depending on the bearing type, the advantages can include, for example, decreased energy loss, improved function under transient abnormal lubrication, increased load-carrying capacity due to more favorable pressure distribution, and the replacement of the currently utilized materials with more sustainable solutions.

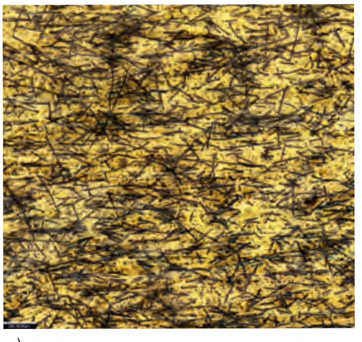
The main target of this task was to study and find the best practices to fabricate durable and well-controlled polymer layered hybrids used in lubricated bearings. The targets and tasks in the project were: 1) the selection of the most feasible polymer material candidates to be used as the functional layer in hybrid bearings, 2) the development of a fabrication technique enabling fabrication of uniform thin layers on metal substrates, 3) the achievement of sufficient adhesion between the polymer and selected substrates, and 4) the fabrication of proto hybrid bearings and a study of their tribological performance with the close-to-real test equipment.

In order to maximize the benefits of the hybrid concept in bearings with functional polymer layers, control of the layer thickness and the polymer properties is essential. The modeling work done in Task 3 also showed that the optimal combinations are typically highly case-sensitive, which means that the polymer layer needs to be highly tailorable. In addition to the thickness of the polymer layer, the properties of the polymer layer can have a strong effect on the performance of a component, such as in Young's modulus, Poisson's ratio, compressive and tensile strength, thermal conductivity, and friction coefficient. All these can be affected by different fillers, and typically the best results in tribological applications are achieved with multi-filler compositions (Orell 2014).

The materials used in the state-of-the-art polymer bearing applications are high-performance thermoplastic polymers, such as polyetheretherketone (PEEK), polyimides (PI), or polyamide-imides (PAI). The processing temperatures and melt viscosities of the materials are normally very high, complicating the achievement of good filler dispersion and the application of thin layers. Moreover, the filler systems can include both micro- and nano-scale particles, making formation of the even dispersion even more challenging.

To avoid problems, solvent casting techniques of a high-performance thermoplastic (PAI) were extensively studied. With the solvent-based techniques, both the mixing and application of the polymer system can be carried out at room temperature, simplifying the fabrication of layered structures with the filled materials. On the other hand, there are certain challenges with the techniques, such as how to ascertain the removal of the detrimental residual solvent. The effect of the residual solvent on the properties was studied using several thermal analysis techniques, and it was shown that with controlled fabrication procedures, these problems can be surpassed. From the results, simple models to estimate the effect on different film properties were derived, enabling extended behavior estimation from a single result, obtained, for example, with dynamic mechanical thermal analysis.

Uniform films made of high-performance polymer (PAI) with different fillers, such as milled carbon fiber, PTFE, and carbon nanotubes, were fabricated (Figure 1a). The thickness of the cast films ranged from 20µm to150µm, which could be controlled in the range of few micrometers. Thermal conductivity and diffusivity of the pure polymer layers were increased by 20–40% with different carbon fillers. On the other hand, although an order of magnitude lower compared to the substrate materials; the thickness of the polymer layer compared to substrates is very small, resulting in the hybrid structures showing similar thermal behavior on a macro-scale. With the combined mechanical and chemical (silane) surface treatment techniques, the adhesion between the applied polymer component and the substrates was significantly improved. Finally, proto bearings were fabricated using the same materials (Figure 1b). The first performance test with the hybrid thrust bearing was promising, and indicated that the adhesion was good enough for the application.


a)


b)

Figure 1. **a) Thin polyamide imide film (thickness of 25µm) filled with milled carbon fiber and PTFE particles, b) PAI-coated thrust bearing**

It can be concluded that the potential material candidate was found, the fabrication technique enabling detailed tailoring with different fillers was proven to be feasible, and the first proto hybrid thrust bearings were fabricated. However, due to problems with the test devices, the tribological performance of the sample bearings could not yet be reliably completed with the planned iterative loops in the testing.

Experimental evaluation of multilayer bearing performance and damage risk

The main goal of experimental testing was to evaluate and improve sliding bearing performance in terms of friction, wear, and smearing, with advanced hybrid and multilayer materials and bearing designs in a variety of operating conditions. Tests and characterization of surfaces also provide fundamental understanding of damage mechanisms and the data to validate the developed calculation model. Successful tests were carried out using lab-scale thrust- and journal-bearing test rigs. Continuously cast leaded tin bronze (CuSn10Pb10) was used as a reference bearing material, as it is widely used in heavy machinery bearings operating in boundary and mixed lubrication regions, due to the excellent dry lubrication properties of lead. In the following, some highlights are presented related to thrust- and journal-bearing tests.

Controlled techniques to apply tailored high performance polymers for functional surface layers in sliding bearings.

Thrust-bearing tests: The load-carrying capacity of a variety of bimetal and bulk polymer bearings was evaluated with a lab-scale thrust-bearing test rig, which simulates the contact conditions in the main thrust bearing of mineral crushers. The oil-lubricated test bearings (Figure 1b) have a flat-on-flat type contact with oil grooves and constant eccentric motion against a case-hardened steel counter-plate under periodically increased axial pressure. The test was continued until a sudden rise in friction, which indicates bearing failure and risk of imminent seizure.

EU-level future restrictions on the use of lead have created an increasing demand for lead-free or low-lead bearing materials. In this task, one special interest was to evaluate the suitability of novel bismuth bronze bimetal material for possible substitution of leaded tin bronze. Table 1 presents the thrust-bearing test results for the bimetal version, where the structure consists of a bronze layer of fine tin-rich and bismuth-rich phases in a copper-rich matrix reinforced by the steel substrate. The main result, describing the load capacity of the bearings, is the final bearing pressure measured when the final failure process begins. The bearings were delivered by Kugler Bimetal SA in cooperation with Metso Minerals.

Table 1. **Thrust-bearing test results**

	Load capacity / Final bearing pressure [MPa]			
Bearing type	1st run	2nd run	3rd run	Average
Reference CuSn10Pb10	8.5	9.0	9.75	9.0
Bimetal CuSn9Bi3Ni2	8.25	9.25	8.75	8.75

Table 1 show that the reference and bimetal bearings performed evenly. The load capacity of the bismuth bronze bimetal bearings was close to that of the reference bearings, and the bimetal showed slightly better running-in behavior. Characterization by electron microscopy showed that the dry-lubricating bismuth precipitations had a fine grain size and an even distribution, which explains the good load-carrying capacity. Both bearing materials experienced polishing wear during the normal test run. It was concluded that the bismuth bronze has the potential to substitute the leaded tin bronzes in the studied operating conditions. A detailed description of the test procedure and the results can be found in reference (Oksanen et al. 2016).

Bismuth bronze has potential for substituting the leaded tin bronzes in heavy duty sliding bearings.

Another test objective was bulk polymer bearings based on polyoxymethylene (POM) and polyamide (PA), provided by Teknikum. The tests with thick polymer bearings changed the overall bearing performance fairly radically. Polymer bearings produced higher frictional torque compared to metallic bearings. This, combined with the modest heat transfer due to the polymers, raised the maximum temperatures of the contact up to high values already with moderate loadings, compared to bronze bearings. However, the test samples were in relatively good condition after testing, with no aggressive failure or seizure marks. In the initial tests, before the modification of the test specimen substrate, it was also revealed from wear traces that the relatively low elastic modulus of the thick (bulk) polymer layer caused very uneven pressure distribution, which was also confirmed with finite element analysis. These tests revealed the importance of lab-scale bearing tests, in which the interplay of material properties and bearing design issues play an essential role in bearing performance. The results also support the observation made in task 3 that polymer layer-based hybrid bearings need to be tailored carefully according to given operating conditions, meaning that they need to be designed correctly in order to get the benefits.

Journal-bearing tests: Different kinds of journal bearing materials were tested, such as bimetal (leaded tin bronze and bismuth bronze castings), bulk bismuth bronze, and multilayer bearings, and these were compared to the reference leaded tin bronze bearing CuSn10Pb10. Various kinds of tests were carried out to evaluate the overall performance of the bearings. In friction and wear tests, the basic idea of testing the material pairs was to establish a Stribeck curve, with the focus on mixed and boundary lubrication conditions, which are always present at least in start-ups and shut-downs of industrial hydrodynamic sliding bearings. It was observed that the good running-in ability of bearing material essentially reduced the friction coefficient in demanding lubrication conditions. In addition, bearing geometrical tolerance was found to have an effect on friction. Tests revealed that bismuth-based bronze bearings have a somewhat similar coefficient of friction to the reference bearing, and they also have good running-in behavior. The results support the view obtained from the thrust-bearing tests that bismuth bronze has the potential to substitute the leaded tin bronzes. Multilayer bearings with a tin antimony sliding layer (delivered by Wärtsilä) had the smallest coefficient of friction, but a relatively high coefficient of friction in the boundary lubrication regime.

Full film lubrication is easily disappearing due to loss in oil feed, which is a major reliability issue in industrial journal bearings. This was studied in smearing tests with appropriate operating conditions, by interrupting oil feed for growing periods of time under full film lubrication. Smearing happens very suddenly and a sudden rise in temperature close to the bearing and frictional torque gives a clear indication of this. Both bimetal, bulk bismuth bronze, and especially multilayer bearings endured much longer before smearing, compared to the reference bearings, although more tests are still needed to improve statistical reliability. A test method was also developed to evaluate bearing ultimate load capacity by increasing projectional pressure step by step in lubricated conditions, until smearing occurred. Initial tests showed good repeatability of the test with multilayer bearings.

Modern test rigs and methods for testing of sliding bearings.

Modeling of hybrid sliding bearing performance

Current demands for higher power density, longer life, and higher energy-efficiency lead to a very challenging operational environment for sliding bearings: higher hydrodynamic pressures, lower film thicknesses, higher temperatures, and increased deformations, all of which need to be taken into account in the design process. Understanding of the deformation behavior becomes even more pronounced when modern hybrid bearing designs with multilayer structures are considered. The main purpose of this task was to develop a parameterized calculation model for hydrodynamic journal bearings, which takes into account hybrid (multilayer) materials, novel bearing designs, shaft misalignment, and elastic and thermal deformations of the bearing surfaces and housings.

The targeted physical features for describing the advanced bearing performance were implemented successfully in the model. The developed model was utilized to evaluate the potential of using a polymer liner in the bearing surface to improve bearing performance, and especially its robustness against shaft misalignment. The model was also used to pinpoint the required liner properties so that, in collaboration with task 1, a suitable material could be tailored. The main idea of a compliant polymer layer is to increase the amount of elastic deformation and therefore reduce the maximum pressure and increase the minimum film thickness. The frequently used bronze bearing was stated as a reference case to which the hybrid bearing performance was compared. Further information about the modeling results can be found in (Linjamaa 2015; Linjamaa et. al. 2016a; Linjamaa et. al. 2016b).

Using the model, hybrid bearing key performance parameters were evaluated in a variety of operating conditions, including shaft misalignment. The following main conclusions can be drawn:

- Elastic and thermal deformations have an effect on the bearing performance, such as maximum hydrodynamic pressure and minimum film thickness.
- Local elastic deformation of the bearing surfaces caused by hydrodynamic pressure was seen to benefit the operation of the loaded journal bearing. The effect of thermal deformation is opposite to that of elastic

> *The developed model is an efficient tool for tailoring the main design parameters of hybrid bearings, in order to obtain full performance benefits.*

deformation. They partly cancel each other out and, depending on the sliding speed and the normal force, either one of them could be more significant.

- Due to the uneven rate of thermal expansion of bearing and shaft surfaces, the overall clearance of the bearing is changed. This indicates that a large thermal deformation of the bearing surface may be harmful to the operation of the bearing as clearance decreases.
- The deformation behavior of the bearing can be altered using hybrid multilayer structures with tailored materials (polymers).
- Hybrid bearings with a compliant polymer layer have good potential, and key performance parameters such as maximum pressure and film thickness indicate an improvement compared to standard bronze bearings.
- Hybrid bearings have the potential to reduce the local maximum edge pressure involved in shaft misalignment cases, as can be seen, for example, in Figure 2.
- Hybrid bearing properties should be tailored carefully according to given operating conditions, meaning that they need to be designed correctly in order to get the benefits.
- Some of the effects of the polymer layer are indirect: like reduced friction caused by reduced clearance, which can be tracked to the low thermal conductivity of the layer.

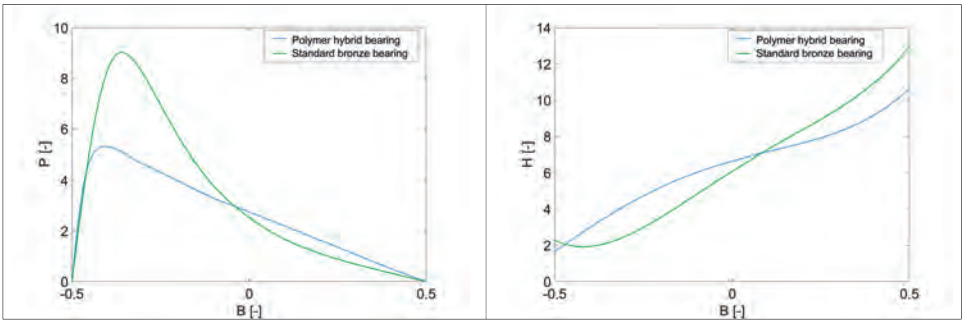


Figure 2. Axial pressure and film thickness profiles of misaligned standard and polymer hybrid bearings with a specific pressure of 12MPa and a sliding speed of 4m/s

The corresponding sliding bearing case with test rig dimensions was also modeled by Wärtsilä experts. The results will be compared to Tampere University of Technology results later.

Figure 2 shows that the polymer layer eliminates high edge pressures of misaligned bearings very effectively. A beneficial increase in film thickness in the area of maximum pressure also occurs. In addition, this deformation shape creates a pocket for the lubricant, preventing it from leaking out of the bearing, further improving the performance of the hybrid bearing in a shaft misalignment case. A similar pocket shape is created in a perfectly aligned case if the hybrid layer has been designed correctly.

Cooperation

The cooperation between the sub-project tasks was intensive, with active cooperation between academic research and the industrial community. Active co-operation also exists with the Hybrids P4 SP1 subproject, related especially to polymer development on sliding surfaces. Successful collaboration was also established with various international sliding bearing manufacturers using advanced materials. A student exchange from TUT to Luleå University of Technology was realized from 1 September 2015 to 28 February 2016. As a result, a joint journal article was accepted to Tribology International.

Conclusions

The research work introduced in this sub-project showed results of great potential and active cooperation between academic research and the industrial community. Development of suitable polymer liner materials for hybrid bearings was carried out successfully, as well as experimental evaluation of lab-scale thrust and journal bearing performances in terms of friction, wear, smearing, and load capacity, using a variety of advanced materials with multilayer structures. A multi-physical calculation model for hybrid journal bearings was developed. It was found that the design of these hybrid bearings is delicate, and their properties must be tailored according to the operating conditions in order to obtain full performance benefits.

Company impact

"From a Metso Minerals company perspective, the current research has brought a lot of important information about the behavior of sliding bearings in different lubrication situations, as well as about the behavior of possible new bearing materials. It is clear that more research is still needed, especially on the advanced simulation of bearings, but also experimental research to verify the simulation results."

Marke Kallio, *senior material researcher, Research & Development, Metso Minerals Oy*

Company impact

"The results of the SLIBE project give tremendous help in modern engine design in terms of new computational tools and testing hardware, which have been developed during the project. Further, the dissertation works give us a deeper understanding of bearing behavior under unusual loads and environments. Modern engines in the near future will need to allow very flexible load profiles, causing special challenges in bearing choices. Now we have a great possibility to validate new materials, designs, and lubricants with the methodology that is developed, and to research special load cases that are impossible or too dangerous (or expensive) to test in a life-size environment"

***Aulis Silvonen,** manager, Materials & Tribology, Marine Solutions, Engines Technology, Wärtsilä Finland Oy*

Outlook

There is a need to continue research and development processes around sliding bearing performance. Even though not realized within the subproject, the utilized solvent-based fabrication technique will enable detailed tailoring of the functional surfaces in the hybrid bearings, including with the high-performance polymers whose fabrication often can be challenging. The dry thickness of a single polymer application layer can be in the range of 2–20 micrometers, making it possible, for example, to fabricate polymer coatings with changing properties in the direction of the coating thickness when solutions with different fillers are applied consecutively. Together with the more efficient and accurate simulation procedures, the techniques enable, in the future, a new scale in the design of bearings with improved functions. The developed sliding bearing model has already been utilized successfully to evaluate the specific features and fundamental behavior of hybrid bearings. However, the operating environment of the engines and machines in which the bearings are involved is moving toward thinner lubricants, higher power densities, and rapid load changes, resulting in very thin film thicknesses and hence mixed and boundary lubrication conditions. That is why bearing surface topography features need to be included in the model, as well as the ability to compute bearing performance in transient, mixed lubrication conditions. In lab-scale bearing experiments, many test methods have already been developed and utilized successfully, but additional features, such as the possibility for film thickness measurement, would provide more accurate verification of the numerical model. The improvements in power density of the studied bearings have also increased the test loading, and at some stage the test rigs themselves should be updated to handle higher power densities. The experimental data provides guidelines for performance comparison between the studied materials and designs, but statistically reliable results call for a more extensive database. To bring the obtained results and bearing performance concepts up to a real product level, these solutions should be tested in large-scale protos in an industrial environment with a controlled test program. This will also give valuable feedback on how to scale up the lab-scale results.

Further information

KEY PUBLICATIONS:

Orell, O. 2014. Polymer Liners in Journal Bearings – Literature Review, DIMECC Report, Tampere University of Technology.

Oksanen, V., Lehtovaara, A., Kallio, M. 2016.Load Capacity of Bismuth Bronze Bimetal Bearing in Lubricated Conditions, Proc. of 17th Nordic Symposium on Tribology, Aulanko, Finland, June 14–17. The updated paper has been submitted to Wear.

Linjamaa, A.2015. Modelling and Analysis of Elastic and Thermal Deformations of a Hydrodynamic Journal Bearing, MSc-Thesis, Tampere University of Technology.

Linjamaa, A. Lehtovaara, A., Kallio, M., Söchting, S. 2016. Modelling and Analysis of Elastic and Thermal Deformations of a Hydrodynamic Radial Journal Bearing. Key Engineering Materials 674(2016), pp. 127–132.

Linjamaa, A., Lehtovaara, A., Kallio, M., Söchting, S. 2016. A. Modelling and Analysis of Elastic and Thermal Deformations of a Hybrid Radial Journal Bearing. Proc. of 17th Nordic Symposium on Tribology, Aulanko, Finland, June 14–17. The updated paper has been accepted to Tribology International.

CONTACT PERSONS:

Marke Kallio/Metso Minerals
Arto Lehtovaara/Tampere University of Technology

PARTICIPANTS:

Metso Minerals, Wärtsilä Finland and Teknikum have been involved in this project, together with two research groups (Tribology and Machine Elements, and Plastics and Polymer Technology) from Tampere University of Technology (TUT)

Mikko Hokka, Veli-Tapani Kuokkala/Tampere University of Technology
Anssi Laukkanen, Kenneth Holmberg/VTT Technical Research Centre of Finland Ltd

Digitalizing materials development

Background

The HYBRIDS program included four industrially focused R&D projects related to the development of new hybrid material solutions and their applications. The development of new breakthrough materials for industrial applications requires a deeper fundamental understanding of material processing, structures, properties, and behavior; a systematic approach to material development; and tools for material structural optimization and design. This was a common need in all four projects, and it is also common in the R&D projects in the simultaneously running DIMECC BSA program related to the development of new advanced steels. The Modeling tools and optimal material design (MTOM) project was a novel instrument in materials research programs, aiming to strengthen science-based and systematic research by taking advantage of the most recent scientific knowhow, methods, and computational tools for material multiscale modeling and simulation. Generic knowledge of materials and their development was used and implanted in the R&D work of projects P1-4 in the HYBRIDS program. A considerable critical mass was achieved by compiling the generic parts in both the BSA and HYBRIDS programs in the FunMode activity. This resulted in an excellent platform for material research at the highest international level. The ambition is to be one of the world leaders in this area after the execution of the program. The MTOM sub-project was a competence project that supports the 10 doctoral projects and the implementation of the results in the industrial problems to be solved, and that glues together generic knowledge on a platform that includes data, methods, and software that can be widely used in material development, due to their generic nature. The main purpose of the MTOM sub-project was to oversee and take part in the core modeling and modeling tools development, as well as the characterization, optimization, and modeling of material properties and the validation of the simulation results needed in the PhD thesis works related to the FunMode project. Integration of the individual PhD thesis works con-

> *Focus on integrated computational materials engineering (ICME) to solve critical industrial research challenges through multiscale modeling.*

ducted in the sub-projects of the HYBRIDS program was carried out to ensure the effective execution and exploitation of the FunMode project. The core modeling development and the definition of modeling strategies were not left solely as the responsibility of specific PhD projects, considering the program-wide synergies and very challenging deliverables. Successful execution and prompt progress of modeling tasks, in order to meet the high ambitions of the program projects, requires considerable modeling project expertise, and PhD projects on their own, without support, are typically too sluggish to meet such constraints. In order to obtain program-wide synergies in modeling, material development, and design, and for the effective exploitation of the results and best practices, such responsibilities were carried by the MTOM sub-project.

Successful modeling and simulation efforts are highly dependent on the quality of the input data. Therefore, it is of utmost importance to obtain accurate enough data on the constituents of the multiphase materials for input into the modeling, as well as on the performance of the resulting entity to validate the quality of modeling. A variety of techniques and methods were used by the participating organizations for the characterization of constituent properties from macro to micro and nanoscale, both when embedded in and when combined with matrix materials. To optimize and customize the use of these materials, thorough, precise, and reliable data on their properties, microstructures, and responses to various service conditions are required in a form that enables the derivation of, for example, engineering design rules. The expanding use of modeling and simulations in the design and use of materials requires that this data is available and in a correct form, such as that described by constitutive and/or phenomenological material models.

The ambition level of MTOM was extremely high, because successful characterization and modeling of the microstructure-property-performance relationships of complex materials is very challenging, as is the simulation of the behavior of these materials under varying and complex conditions. This work is internationally groundbreaking and requires wide collaboration between both Finnish and particularly international partners and networks.

Digitalized materials engineering speeds up product development and brings predictability and reliability for demanding applications.

Objectives

The goal of MTOM was to derive a modeling concept and package for the FunMode projects and the industry-driven projects of the HYBRIDS program, and to ensure and aid in the effective implementation of modeling-related tasks. This was done by utilizing the identified state-of-the-art means and tools, and further developing the identified areas where the greatest impact can be obtained and is required, and by tightly integrating the modeling activities within the programs. The existing solutions and previous work, know-how, contacts, and networks of the partners were included in the sub-project. The result provided a platform for multiscale modeling tools developed during the run of FunMode applied to solve specific modeling problems within the programs, and gathered the computational tools related to development under a single banner to be further exploited, developed, and disseminated. The MTOM sub-project oversaw the implementation of modeling activities within FunMode and integrated them both directly and via PhD works in the modeling work carried out in the BSA and HYBRIDS program's projects. In order to utilize the above-mentioned modeling tools to the full extent, the aims of the characterization and validation part of MTOM were:

1) to produce generic material data and material behavior information on materials' responses to various mechanical, physical, and chemical stimuli in different conditions,
2) to build material models based on the generated data to be used in modeling tool development and simulations,
3) to develop and apply new validation methodologies and equipment to verify the material models, modeling approaches, and simulation results,
4) to generate practical design rules based on the above research work.

After finishing this part of MTOM, Finnish industry has, for its use, a large database on the properties, microstructures, and behavior of the novel materials developed in the HYBRIDS projects, accurate multi-parameter material models to be used in simulations of the behavior of the developed materials, methodologies and devices to validate the modeling and simulation results, and design rules to facilitate efficient and correct use of the studied materials and structures.

The particular subject areas identified for MTOM in the HYBRIDS program, on the basis of the PhD works, were the following:

i) Process-structure-properties-performance multiscale modeling and fundamentals of multifunctional coatings and composites,
ii) Multiscale and multiphysical modeling of multifunctional hybrid structures,
iii) Tribological applications of hybrid polymer composites.

Key results and impacts

Most of the work carried out in MTOM aimed to provide projects and PhD efforts with advanced modeling and characterization research resources to improve their ability to tackle complex subject areas and ramp up the development and introduction of new capabilities. Highlights of selected key results related to MTOM tasks and their impacts are summarized in the following, focusing on results that are the prime deliverables of MTOM.

T1 Methodology and compilation

One of the primary objectives of T1 was the introduction of next-generation tools for modeling material structure for engineering material property correlations and causalities. The same tools can be further expanded to evaluate material performance under more complex functional environments. To that effect, a microstructural modeling methodology for hybrid and composite materials was generated, and typical models are presented in Figure 1. As an outcome, a very general and extensible microstructural modeling capability has been compiled, which can be utilized for hard material composites, as well as polymer-based reinforced and filled multiphase composites. The input data for such models can be treated in a versatile manner, meaning that the data can be statistical in nature, or, for example, 3D imaging data, such as tomography, electron back-scatter diffraction, or atom probe data. In addition to being able to create nano-microstructural models, effort was put into creating abilities to modify the models, to be able to carry out virtual material design tasks and trials.

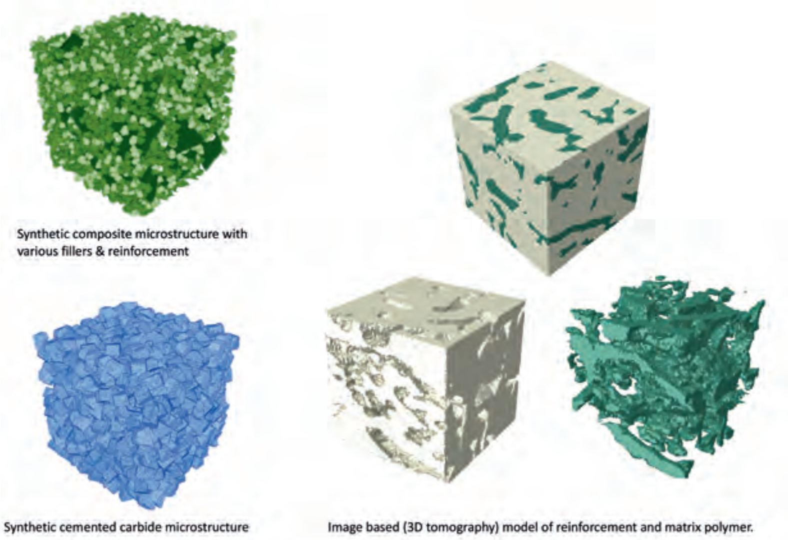


Figure 1. Three examples of microstructures developed with the microstructural modeling methodology

T2 Supporting doctoral project modeling development

Effort was put into supporting the PhD thesis works related to the other projects in the HYBRIDS program. The research work was carried out in collaboration with experimental, and modeling and simulations groups for better output. An example is presented below, in which the toolsets of T1 were applied to develop microstructural models of composites based on carbon fiber-reinforced polymer (CFRP). A modeling case was developed, validated, and applied to study the mechanical response and significance of microstructural features to the properties and performance of the material solution (Figure 2).

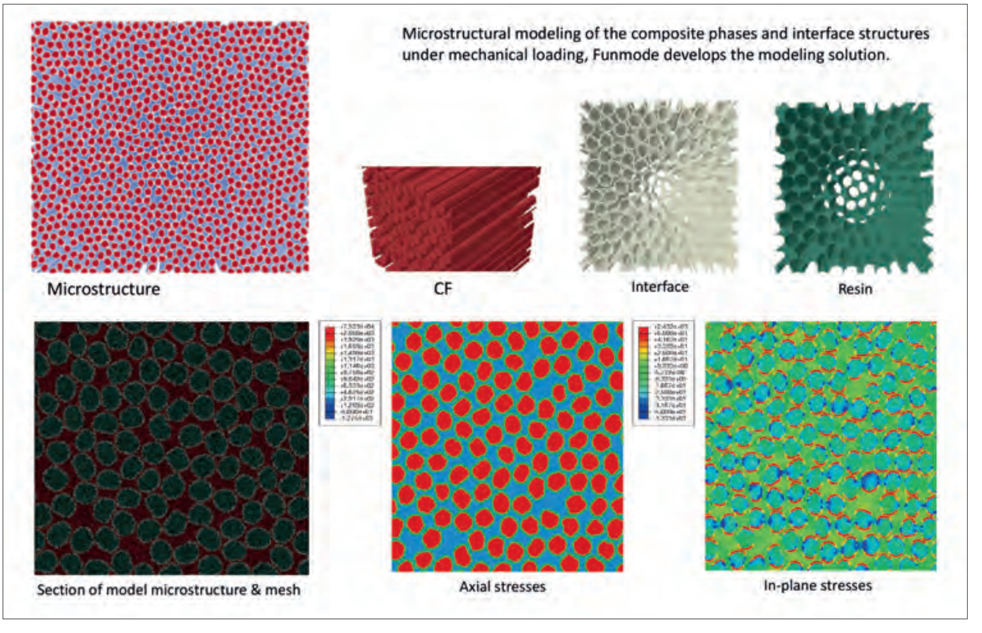


Figure 2. **CFRP microstructural models and case modeling result**

T3 Building of generic modeling toolkits

Modeling toolkits were developed to support individual projects and PhD works. The toolkits were thematic, meaning that solutions served a particular area with respect to delivering a novel new capability not previously in existence. The typical nature of a project need was that the solution to the affiliated problem can be significantly influenced if the suitable design abilities are possessed to create the knowledge to do so, while simultaneously tackling the costs and time required to solve the problem in question. Two examples are presented in the following: the design of hard material composites (Figure 3) and the modeling of tribological contacts, including the topography of surfaces (Figure 4).

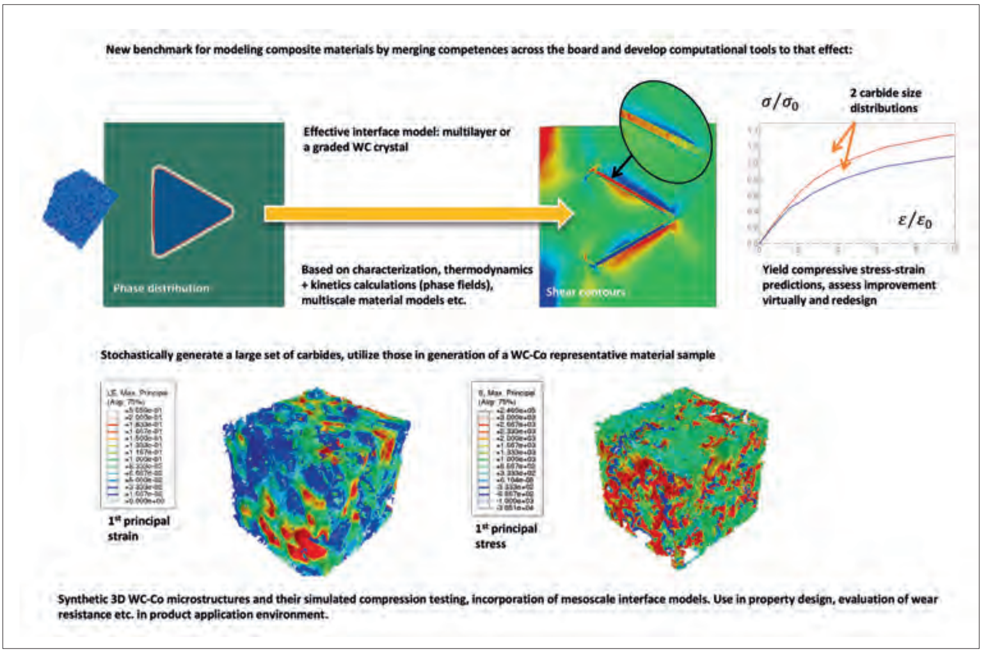


Figure 3. **Process-structure-properties-performance toolset for powder metallurgical composites**

The solution for powder metallurgical hard material composites involves a modeling solution that comprises the complete process-structure-properties-performance (PSPP) chain, deemed at present to be the future approach to meeting material solution-affiliated design challenges. For PM materials such as hard material composites, the strength in the approach is the ability to run manufacturing process design trials in the computational environment, and to propagate these results to evaluate engineering material properties or material performance under more complex conditions, such as when subjected to tribological contact. As such, it is possible to tailor, for example, the manufacturing process and alloy composition to meet a specific product-driven performance need, which by conventional means is very costly and time consuming. The methodology is extensible and is envisioned to provide the capabilities for material and manufacturing process design for future industrial manufacturing methods, primarily metal additive manufacturing. Another example toolset is presented in Figure 4. Several projects worked on understanding the significance of surface character for various product performance dominating mechanisms, such as the initiation and growth of fatigue cracks and the behavior of material solutions under tribological contacts. To that effect, a toolset was introduced to create numerical models either statistically based on roughness data, or directly, based on measured surface topographies. The capability can be tied to microstructural modeling capabilities, enabling the study and exploitation of microstructural material details, surface topography, and their interactions in designing, for example, better wear-resistant surfaces.

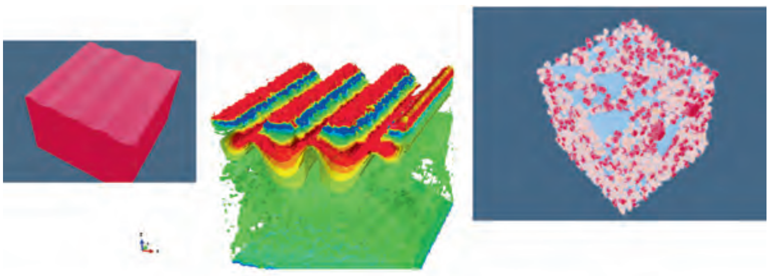
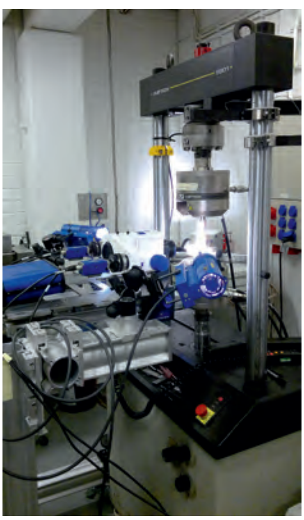


Figure 4. **Surface topography and microstructure modeling toolset**



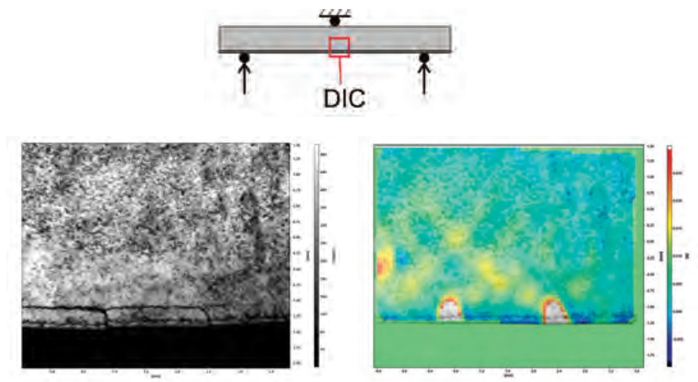


Figure 5. **Mechanical loading of wear-resistant coatings with in-situ digital image correlation (DIC)**

T4 Characterization for modeling input data

Characterization efforts were carried out directly linked to modeling affiliated developments and vice versa. Numerous cases were studied, and an example of mechanical loading of wear-resistant coatings with in-situ digital image correlation (DIC) is presented in Figure 5. In this case, the challenge was to study the interaction between the coating and the substrate material, and to establish what the damage and cracking mechanisms of the coated system are under various modes of loading. Implementation of DIC testing for this case enabled the establishing of the actual failure mechanisms of the material solution.

T5 Testing and validation

Testing and validation of the models and simulations was carried out throughout the project. Fracture, fatigue, and wear behavior of various materials were studied, and a new methodology was developed for the analysis of material behavior. In particular, image-based measurements such as DIC and infra-red measurements were developed to match the research needs of the projects. These measurements not only give new information on material behavior, but can also be used for verification of the simulation models. The strain information obtained with the DIC can be compared to the simulation results for quantitative verification of the material model. An example of dynamic punch testing of coated specimens is presented in Figure 6, displaying the capabilities of the DIC to resolve the mechanical behavior of a component in a relevant testing environment, producing information with respect to both component response and a validation case for modeling.

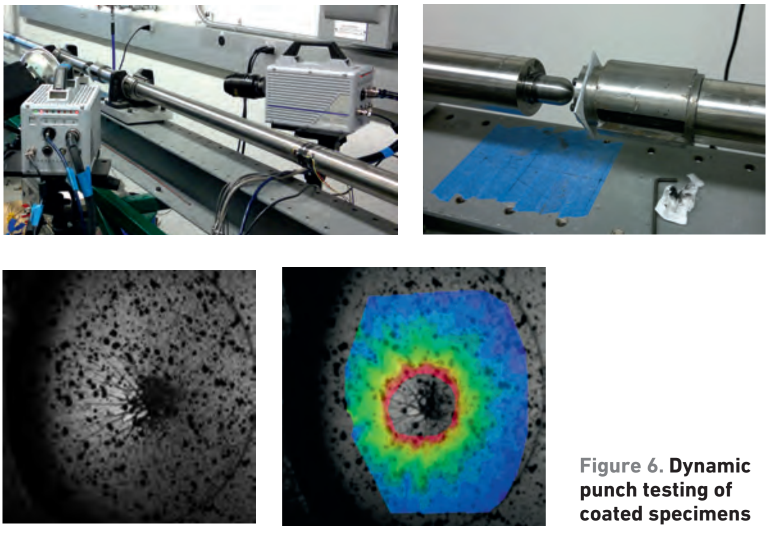


Figure 6. **Dynamic punch testing of coated specimens**

Summary and outlook

The original aims of the project were reached only partially, due to the untimely ending of the project. For this reason, the work was also focused primarily on supporting the PhD theses of those students who had realistic possibilities to graduate within the shortened duration of the HYBRIDS program. Dissemination activities and development of some of the more complex solutions were left in a partially complete state. Despite this, the results obtained from the project have significantly pushed forward the state of the art in material modeling. The work has especially reduced the gap between laboratory and full industrial-scale research, improving the understanding of material behavior in many demanding applications, and providing new reliable data on the properties and microstructures of existing and newly developed materials to be used in industrial products. Many of the experimental observations can now be better explained and quantified with the help of multiscale modeling, which can further be used for the generation of design criteria for the advanced development and utilization of the new materials. MTOM has had a significant impact on the scientific level of the PhD theses being prepared in the DIMECC Breakthrough Materials Doctoral School. As a result, more sophisticated and demanding experiments have been carried out, and more challenging modeling problems have been solved with the help of the experienced MTOM scientists. The impact of MTOM will not be limited to the scope of the project, but the knowledge and competence built during the project will carry much further into the future. As a competence-building project, the work is never completed or finished. The outlook of the work is to further develop the understanding of process-structure-property-performance relationships of the most important structural materials.

An important part of MTOM was the national and international cooperation within the project. A lot of work was carried out in collaboration with companies, research centers, and universities around the world, and most of the publications include co-authors from international partners. The extensive collaboration has increased the scientific level of the research and improved the impact of the results. The results of MTOM have gained international recognition, for example, in numerous keynote and invited presentations. The MTOM project established links to the major global Integrated Computational Materials Engineering programs, the Materials Genome Initiative (MGI) in the US, and Structural Materials for Innovation (SM4I) in Japan, and networked with European networks such as the European Materials Modeling Council (EMMC). Research methods and the developed new materials have already been used in other international projects. Following the project, a global network of colleagues and collaborators now exists, ready to plan new state-of-the-art research projects.

Further information

KEY PUBLICATIONS:

Laukkanen, A., Andersson, T., Pinomaa, T., Holmberg, K., "Effective interface model for design and tailoring of WC-Co microstructures", Journal of Powder Metallurgy, 59, 2016, pp. 20–30.

Suhonen, T., Laukkanen, A., Andersson, T., Pinomaa, T., Holmberg, K., "Proper-Tune – Computational Multiscale Materials Modeling Concept", Thermal Spray Bulletin, 68 (2), 2016, pp. 102–106.

Holmberg, K., Laukkanen, A., Ronkainen, H., Waudby, R., Stachowiak, G., Wolski, M., Podsiadlo, P., Gee, M., Nunn, J., Gachot, C., Li, L., "Topographical orientation effects on friction and wear in sliding DLC and steel contacts, Part 1: experimental", Wear, 2015, 330, pp. 3–22.

Laukkanen, A., Holmberg, K., Ronkainen, H., Waudby, R., Stachowiak, G., Wolski, M., Podsiadlo, P., Gee, M., Nunn, J., Gachot, C., Li, L., "Topographical orientation effects on friction and wear in sliding DLC and steel contacts, Part 2: modeling", submitted to Wear, 2016.

V.-T. Kuokkala J. Seidt, J. Smith, E. Sarlin, A. Gilat, "Investigation of the Thermal-Mechanical Response of a Hybrid Material in Dynamic Loading Conditions". 2016, International Conference on Experimental Mechanics.

Kiilakoski, Jarkko; Lindroos, Matti; Apostol, Marian; Koivuluoto, Heli; Kuokkala, Veli-Tapani; Vuoristo, Petri, "Characterization of High-Velocity Single Particle Impacts on Plasma-Sprayed Ceramic Coatings", Journal of Thermal Spray Technology, 2016, pp. 1–11.

CONTACT PERSONS:

Mikko Hokka, Veli-Tapani Kuokkala/Tampere University of Technology

Anssi Laukkanen, Kenneth Holmberg/VTT Technical Research Centre of Finland Ltd

PARTICIPANTS:

Tampere University of Technology, VTT Technical Research Centre of Finland Ltd, Aalto University

FUNDAMENTALS AND MODELING

P5
SP2

Markku Heino/Spinverse
Mikko Hokka, Veli-Tapani Kuokkala/Tampere University of Technology
Kenneth Holmberg, Anssi Laukkanen/VTT Technical Research Centre of Finland Ltd

DIMECC Breakthrough materials doctoral school

Background

The development of new breakthrough steel and hybrid materials solutions for industrial applications requires a deeper fundamental understanding of material processing, structures, properties, and behavior; a systematic approach to material development; and tools for material structural optimization and design. Better competitiveness requires a shorter time to market for new products.

The DIMECC Breakthrough Materials Doctoral School was built as an integrated part of the Fundamentals and Modeling cross-cutting project (FunMode) included in the two materials programs, DIMECC BSA and HYBRIDS. This was a new instrument in materials research programs, aiming to strengthen science-based and systematic research by taking advantage of the most recent scientific know-how, methods, and computational tools for material multiscale modeling and simulation. The project was generic in nature and cross-cutting, so that it supported each of the more industrially oriented projects. The critical mass was increased by joint research work, mentoring, and collaboration with similar FunMode projects included in both programs.

A multidisciplinary group of doctoral students, their mentors, top international research partners, and key industrial experts, together solving critical research challenges defined with the industry.

This has created unique solutions and competence for application-driven digital materials engineering serving Finnish industry.

Objectives

The scientific goal was to create new science-based innovative material solutions suitable for industrial applications, and to develop and utilize new material modeling and simulation techniques and software tools of world class that are based on a deep fundamental understanding of material processing, structures, properties, and performance. The objective was to achieve this by carrying out a set of 28 coordinated doctoral thesis works in areas directly linked to the other projects in the programs.

The doctoral subprojects were an integral part of the research work in the industrially driven parts of the programs, and thus increased the understanding and scientific basis for material development and tailoring for specific purposes by systematic computational modeling and simulation. The objective was that participating companies would learn a systematic computational material modeling and simulation-based technique for material optimization and design, and get access to relevant methods and software tools.

Key results and impacts

The Doctoral School started successfully in 2014 with 28 doctoral students financed by the two programs DIMECC BSA and HYBRIDS. The topics for PhD work were selected by the involved companies, and the work of the doctoral students was integrated as a part of the research plan of the industrially driven projects in the two programs. There was a great interest in this new concept of an industrially driven academic doctoral school with a strong emphasis on new, advanced material digitalization techniques. During the first years, 10 other PhD students working with various funding on closely related topics applied to join the Doctoral School and were approved as associate members. They brought complementary competence to the Doctoral School and widened the scientific and technological interactions and networks by participating in our workshops and meetings. All doctoral projects include a visit to some internationally top-level university or research institute abroad for a period of about 6 months.

One special feature of the Doctoral School is that it runs in parallel with the FunMode competence project, in which new, world-class solutions were developed and studied both on multiscale integrated material modeling and associated advanced methods, to provide relevant input data for the modeling and validation of the models. The doctoral students were in continuous communication with the top scientists in the competence project and worked with them on, for example, developing new software, new measurement techniques, and characterization methods. The results have been jointly published in top journals. *With this mechanism, the doctoral students did not need to start on, for example, relevant modeling issues from scratch, but could quickly absorb state-of-the-art knowledge and from there start to tackle their own scientific challenges.*

The Doctoral School was a learning platform where top experts in materials science from four Finnish universities and the research center VTT, together with some invited scientists from, for example, France and the USA, offered new technologies, scientific understanding, and direct support to the doctoral students in their work on focused industrial problems. This was arranged in the form of six larger seminars, including special topical sessions, workshops, and meetings.

The Doctoral School and the doctoral subprojects were planned for five years. After three years, by the end of 2016, the status of the Doctoral School was as follows:

- it included 20 BSA doctoral students and 8 HYBRIDS doctoral students,
- 10 doctoral students with external funding had joined,
- 5 successful dissertations have been completed: Antti Kaijalainen, University of Oulu (UO); Matti Lindroos, Tuomo Nyyssönen, Juuso Terva, Elisa Isotahdon, Tampere University of Technology (TUT)
- 112 journal articles had been published,
- 12 research work periods abroad over several months had been made to the following countries: Canada, Australia, France, Germany, Austria, the Netherlands, Norway, Portugal, UK, USA,
- 6 DIMECC Breakthrough Materials Doctoral School seminars were arranged with, on average, 46 participants (active theme sessions, coaching, interlinking of projects, dissemination of results).

Below are some examples of novel tools jointly developed in the FunMode competence project by top scientists and doctoral students during the first two years of international collaboration with leading laboratories worldwide. Most of them are at a very promising proof-of-concept level, and several article drafts are under work.

Examples of novel software, measurement, and characterization tools developed so far in FunMode, with the main partners given, are:

- an integrated FEM microstructural-topographical multiscale material model (nano-micro-macroscale) based on real measured fractal topography data and microstructure SEM images, applied to polymer-based composite, diamond-like carbon (DLC) coated steel and steel surfaces, VTT, Curtin University, Perth, Australia, *Figure 1a,*
- a characterization, thermodynamics, and phase field kinetic calculations-based multiscale material model with advanced interfacial behavioral representation for WC-Co cemented carbides, VTT, McGill University, Montreal, Canada, *Figure 1b*,
- a multiscale process-microstructure-properties phase field material model for the droplet collision, and splat initiation and microstructural growth of Cr_2O_3-TiO_2 thermal spray coatings, VTT, McGill University & Canmet, Montreal, Canada, *Figure 1c*,
- a crystal plasticity microstructural material model for representing complex metallic microstructures and their properties and support design rule development for complex loading conditions, VTT, TUT, Ecole de Mines, Paris, France, *Figure 1d*,

- **a method for reconstruction of austenite microstructure and orientations from martensitic electron backscatter diffraction (EBSD) data**, TUT, Colorado School of Mines, USA, *Figure 2a*,
- **a method for characterization of surface cracks on a fractal level in rocks** and their effect during dynamic and quasi-static loading, TUT, University of Potsdam, Germany,
- **enhanced constitutive equations for predicting the strength of Nordic granites** in dynamic loading compression and triaxial confinement, TUT, Purdue University, Indiana, USA, SINTEF, Trondheim, Norway, *Figure 2b*,
- **a method for synchronous full-field measurement of strain and deformation-induced heating** during low, intermediate and high strain-rate tensile experiments, TUT, Ohio State University, USA, *Figure 2c*,
- **a technique for adhesion measurement of composite thermal spray coatings** with in-situ digital image correlation (DIC), TUT, 2d,
- **a technique to characterize and model the toughness properties of ferritic-austenitic stainless steels** containing metastable austenite, UO, VTT.

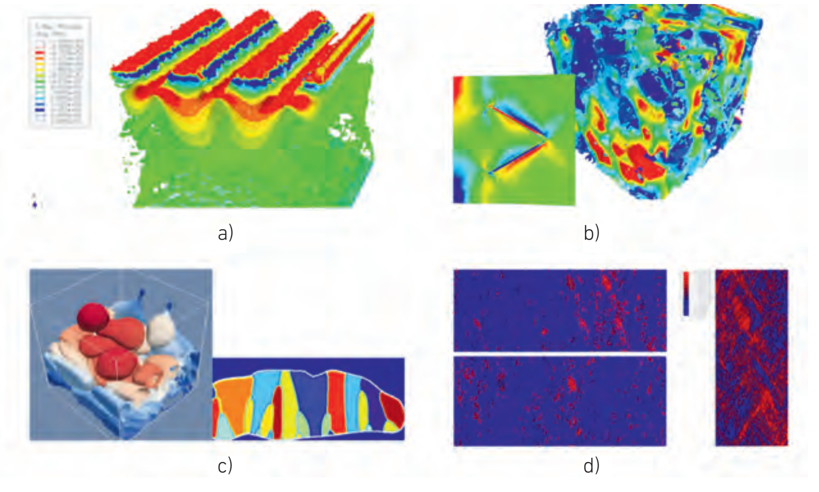


Figure 1. Novel software tools for material digitalization and performance simulation developed in the FunMode project: a) an integrated topography-microstructure fractal multiscale surface model, b) a thermodynamic and phase field-based multiscale model for WC-Co cemented carbides, c) a process-microstructure-properties phase field material model for droplet collision and splat imitation of thermal spray coatings, and d) a crystal plasticity microstructural material model for complex metallic structures

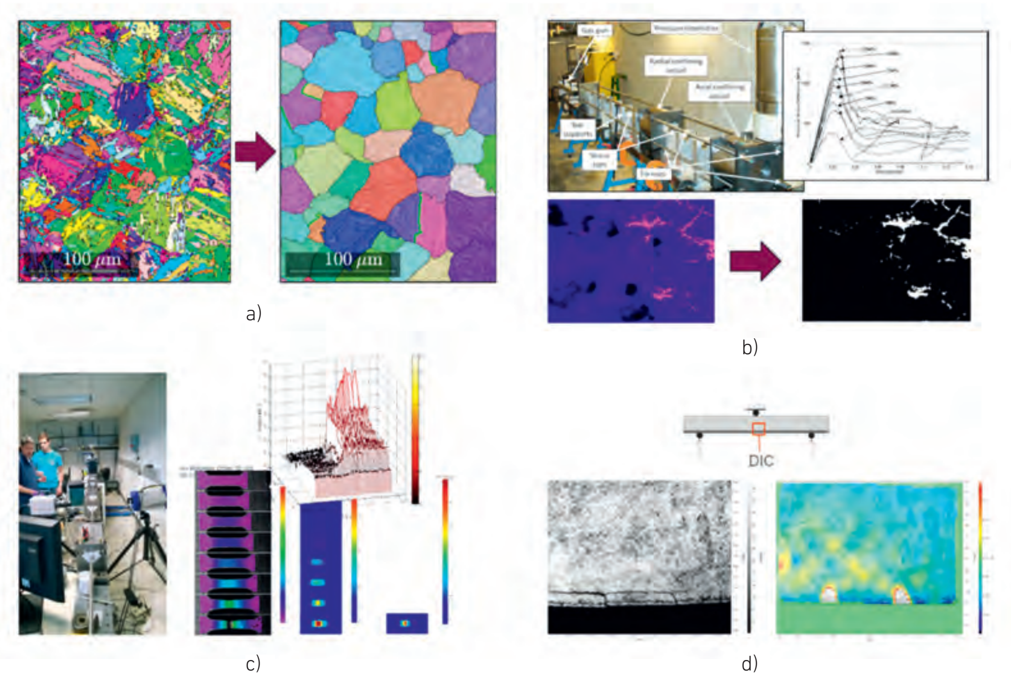


Figure 2. **Novel characterization, measurement and testing techniques for digital material data generation developed in the FunMode project: a) reconstruction of austenite microstructure and orientations, b) a model for predicting the strength of granite at dynamic loading, c) synchronous full-field measurement of strain and deformation-induced heating in tensile experiments, and d) adhesion measurement of composite thermal spray coatings with in-situ digital image correlation**

External expert view

"I was very pleased to be a participant in the scientific sessions of the DIMECC Breakthrough Materials Doctoral School event for several reasons. I am personally convinced that industrial needs can be the source of very nice scientific problems, so that a strong partnership between companies and universities is one of the keys for excellent applied research in the field of advanced engineering. The purpose of DIMECC is exactly to develop this type of interaction. I was impressed to see that the whole Finnish community is involved in the program, with many companies, with large funding and enough time to generate strong links between people on each side.

Obviously the result is excellent. This was demonstrated by the quality of all the presentations by the students. The seminar offers the opportunity for older students to summarize their work and for beginners to open their eyes to the large research field covered by the doctoral school. The subjects are all motivated by industrial application and they generally include an important testing part. In some cases, a suggestion would be to introduce a little bit more numerical simulation, but this might be a difficult task, since the topic is the real world with a lot of interacting physical rules and complex thermomechanical states. Clearly the position of the group is at the cutting edge of the field."

Prof. ***Georges Cailletaud,***
École Nationale Supérieure desMines de Paris, Centre des Matériaux

External expert view

"I enjoyed participating in the DIMECC Breakthrough Materials Doctoral School seminar. The idea of having the students presenting their progress and being questioned by their peers and professors is a great one. I found the students to be very professional, attentive, and eager to learn more."

*Prof. **Amos Gilat**, Ohio State University, USA*

Company impact

"Material technology has a key role in developing future minerals processing solutions at Metso. Material research, together with experimental field testing and the latest digital technologies, gives us a lot of opportunities to develop more sustainable and cost-efficient solutions. Learning from each other is an important part of the development."

***Jari Riihilahti**, VP Technology at Metso*

CONTACT PERSONS:

Markku Heino/Spinverse

Kenneth Holmberg, Anssi Laukkanen,
VTT Technical Research Centre of Finland Ltd

Mikko Hokka, Veli-Tapani Kuokkala,
Tampere University of Technology

PARTICIPANTS:

VTT Technical Research Centre of Finland Ltd, Tampere University of Technology, Aalto University, Lappeenranta University of Technology, University of Oulu

List of publications

HYBRIDS P1 Multifunctional thin coatings

Xiaoxue Zhang, Saara Heinonen and Erkki Levänen: Applications of supercritical carbon dioxide in materials processing and synthesis, RSC Advances vol. 4, 2014, 61137.

J. Nikkola: Microcapsule-protected actives reduce leaching European Coatings Journal, 2014-4, 36–40.

Mikko Långvik, Kauko Jyrkäs, Antti Markkula, Meri Rosenberg: Uusi T-taivutusmenetelmä maalipinnoitettujen terästen muovattavuuden tutkimiseksi eri lämpötiloissa, Ohutlevy-lehti, Helsinki: Teknologiainfo Teknova Oy, 1239-4122, 2015:2, s. 15–18.

J. Leppaniemi, J. Lyytinen, O. Elomaa, K. Suomalainen, J. Koskinen: The influence of PVD coatings on the wear performance of steel dental curettes, Key Eng. Mat. 674 (2016) 289–295.

Leena Vuori, Harri Ali-Löytty, Kimmo Lahtonen, Markku Hannula, Elina Lehtonen, Yuran Niu, Mika Valden: Improved corrosion properties of Hot Dip Galvanized Steel by nanomolecular silane layers as hybrid interface between HDGS and top coatings, Corrosion, Vol. 73, No. 2, 2017.

J. Leppaniemi, P. Sippola, M. Broas, J. Aromaa, H. Lipsanen, J. Koskinen: Corrosion protection of steel with multilayer coatings: improving the sealing properties of PVD CrN coatings with Al_2O_3/TiO_2 ALD nanolaminates, submitted for publication, Thin Solid Films.

J. Leppaniemi, S. Hoshian, K. Suomalainen, T. Luoto, V. Jokinen, J. Koskinen: Non-stick properties for dental restorative instruments by thin film coatings, submitted for publication, European Journal of Oral Sciences.

J. Leppaniemi, T. Sarikka, P. Sippola, H. Lipsanen and J. Koskinen: Investigation on Atomic Layer Deposition coating adhesion on steel using adapted Rockwell indentation, submitted for publication, Thin Solid Films.

T. Varis, P. Vuoristo: Thermal sprayed metal coatings, to be submitted.

R. Mahlberg: Sol-Gel passivation on Hot Dip Galvanized steel, to be submitted.

T. Vuorio: Algae growth on Color Coated Steels, to be submitted.

V. Saarimaa, A. Kaleva, J-P Nikkanen, S. Heinonen E. Levänen, P. Väisänen, A. Markkula, J. Juhanoja: Artificial patina growth on Hot Dip Galvanized steel 1, to be submitted.

A. Kaleva, V. Saarimaa J-P Nikkanen, S. Heinonen, P. Väisänen, A. Markkula, E. Levänen: Nanorod formation of zinc corrosion products on galvanized sheet in supercritical carbon dioxide, to be submitted.

R. Mahlberg: Improved abrasion resistance of polymeric substrates with hybrid sol-gel coatings, to be submitted.

P1 Conference papers

E. Lehtonen, L. Vuori, M. Hannula, K. Lahtonen, H. Ali-Löytty, M. Ahonen, M. Hirsimäki, H. Karjalainen, A. Rantamäki, E. J. Saarinen, J. Lyytikäinen, T. Niemi, O. G. Okhotnikov, and M. Valden: Surface modification and analysis methods at molecular level, Abstracts of the 28th International Conference on Surface Modification Technologies, STM28, Tampere University of Technology, Tampere, Finland, June 16–18, 2014.

V. Saarimaa: Thin Organic Coatings on Hot Dip Galvanized Steels, seminar presentation in Nordic European Coil Coating Association, Borlänge, Sweden, 2014.

L. Vuori, E. Lehtonen, K. Lahtonen, M. Hannula, H. Ali-Löytty, M. Hirsimäki, P. Jussila, P. Väisänen, A. Markkula, and M. Valden: Interfacial Silane Monolayers for Enhanced Corrosion Protection and Adhesion Properties on Hot Dip Galvanized Steel, NANOSMAT conference 13.–16.9.2015 Manchester, UK.

Mikko Långvik, Kauko Jyrkäs, Antti Markkula, Meri Rosenberg: New T-bend testing method to examine formability of color coated steel sheet in different temperatures, Proceedings of the METNET Seminar 2015 in Budapest / Kuldeep Virdi and Lauri Tenhunen (editors). Hämeenlinna: HAMK University of Applied Sciences, 2015. (HAMKin e-julkaisuja, 1795-424X, 30/2015), 978-951-784-763-6, s. 102–111.

Kaleva A., Heinonen S., Nikkanen J-P., Levänen E.: Synthesis and crystallization of titanium dioxide in supercritical carbon dioxide ($ScCO_2$). IOP: Conference Series: Materials Science and Engineering. Accepted to IOP. The 4th International Conference on Competitive, Materials and Technology Processes, 175 (2017) 012034.

M. Sorvali, J. Haapanen, L. Vuori, M. Pudas, M. Valden, J.M. Mäkelä: Multilayered omniphobic coating on stainless steel based on aerosol nanoparticle synthesis, to be submitted to European Aerosol Conference 2017.

P1 Theses

Helen Marjukka: Modification of polymer and metal surfaces using supercritical carbon dioxide, M.Sc. Thesis, Materials Science TUT, 2015.

Turppa E.: Kuumasinkityn teräspinnan puhdistus ja funktionalisointi APS-silanoinnilla, B.Sc. Thesis, Tampereen teknillinen yliopisto, 2015.

Lagus M.: Formability-related Studies of Color Coated Steel (SSAB Europe), B.Sc. Thesis, Åbo Akademi University, 2015.

Lehtonen J-M: Optimization of the first coating layer on TOC-based Coil Coatings Steel" (SSAB Europe) M. Sc. Thesis, Materials Science TUT, 2015.

Kaleva A: Utilization of supercritical carbon dioxide in titanium dioxide synthesis and aerogel manufacturing, M.Sc. Thesis, Materials Science TUT, 2016.

Haikola S.: Metalliohutlevyjen maalien heijastavuus lähi-infrapunasäteilyn alueella, M. Sc. Thesis, Aalto University, 2017, to be submitted.

Sorvali M.: Omnifobisuuden tuottaminen teräksen pinnalle kerrosrakenteisella nanopinnoitteella, M. Sc. Thesis, Department of Aerosol Physics TUT, 2017.

P1 Reports

Kaleva A: Lämmönhallintapinnoitteiden valmistaminen ylikriittisen hiilidioksidin avulla, Literature survey, Tampereen teknillinen yliopisto, 2014.

Jarmo Leppäniemi: Biomimetic structures for high grip surfaces, Literature survey, Aalto University 2015.

Minna Kotilainen, Petri Vuoristo: technical report –adding colorant agents into molten zinc and definition of particles to ald coatings, TUT, D1.2 and D1.3 / 2015.

Minna Kotilainen, Mikko Kylmälahti, Tommi Varis, Petri Vuoristo: technical report –thermal sprayed dyed/coloured coatings, TUT, D1.1: Technical report/2015.

HYBRIDS P2 Multifunctional thick coatings and composites

V. Matikainen, H. Koivuluoto, P. Vuoristo, Microstructural Characteristics Of Different Cr3C2 Coating Compositions Sprayed with HVAF Process, The Twenty Eighth International Conference on Surface Modification Technologies, Valardocs, 28, 2015, p. 77–87.

J. Silvonen, V. Ruusila, E. Levänen, M. Uusitalo, Influence of application method and sintering temperature on porosity and thermal conductivity of two commercial silicon carbide based castables, UNITECR2015 – 14th Biennial Worldwide Congress, 224, 2015.

J. Laurila, P. Vuoristo, O. Tuovinen, M. Uusitalo, Surface Reactions of Single Crystal Diamonds with Chromium Containing Nickel-based Braze Materials, IBSC 2015, Long Beach CA, USA.

A. Milanti, Characteristics of Iron-based Thermal Sprayed Coatings Manufactured with High Velocity Oxygen Fuel and High Velocity Air Fuel Spraying for Wear and Corrosion Applications, Doctoral Thesis, Tampere University of Technology, Tampere, Finland, 2016, 215 p.

V. Matikainen, G. Bolelli, H. Koivuluoto, P. Sassatelli, L. Lusvarghi, P. Vuoristo, High-temperature sliding wear behaviour of thermally sprayed Cr_3C_2-based coatings, The 17th Nordic Symposium on Tribology – NORDTRIB 2016, Hämeenlinna, Finland, 10 p.

J. Kiilakoski, M. Lindroos, M. Apostol, H. Koivuluoto, V.-T. Kuokkala, P. Vuoristo, Characterization of High-Velocity Single Particle Impacts on Plasma-Sprayed Ceramic Coatings, Journal of Thermal Spray Technology, 25(6), 2016, p. 1–11.

V. Matikainen, K. Khanlari, A. Milanti, H. Koivuluoto, P. Vuoristo, Spray parameter effect on HVAF sprayed (Fe,Cr)C-30FeNiCrSi hardmetal coatings, International Thermal Spray Conference & Exposition, ITSC 2016, DVS Media GmbH, Shanghai, China, 2016, p. 184–189 6 p.

J. Kiilakoski, A. Lutoschkin, M. Plachetta, M. Apostol, H. Koivuluoto, A. Killinger, P. Vuoristo, Fracture Characteristics of High-Velocity Suspension Flame-Sprayed Aluminum Oxide Coatings, International Thermal Spray Conference & Exposition, ITSC 2016, DVS Media GmbH, Shanghai, China, 2016, p. 466–471.

S. Nevezhin, D. Fantozzi, I. Malygina, Y. Korobov, A. Milanti, H. Koivuluoto, P. Vuoristo, A. Makarov, M. Filippov, Study of High Velocity Arc Sprayed heat resistant coatings from FeCrAlBY cored wire, International Thermal Spray Conference & Exposition, ITSC 2016, DVS Media GmbH, Shanghai, China, 2016 p. 852–856.

M. E. Cura, V. K. Singh, P. Viitaharju, J. Lehtonen, S.-P. Hannula, Pulsed Electric Current Sintered Cr_2O_3-rGO Composites, Key Engineering Materials, 721, 2017, p. 419–424.

D. Fantozzi, V. Matikainen, M. Uusitalo, H. Koivuluoto, P. Vuoristo, Chlorine-induced high temperature corrosion of Inconel 625 sprayed coatings deposited with different thermal spray techniques. Surface and Coatings Technology, 2017, 11 p., published online.

H. Koivuluoto, U. Kanerva, Termisellä ruiskutuksella monitoiminnallisia pinnoiteratkaisuja vaativiin teollisuuden käyttökohteisiin, Hitsaustekniikka, 1, 2017, p. 17–19.

HYBRIDS P3 Transition towards Circular Economy – life cycle perspective in material development

Husgafvel, R. Pajunen, N. Virtanen, K. Paavola, I-L. Päällysaho, M. Heiskanen, K. Dahl, O. and Ekroos, A. 2015. Social sustainability performance indicators – experiences from process industry. International Journal of Sustainable Engineering. DOI:10.1080/19397038.2014.898711.

Mäkikoskela, R. 2015. Ympäri, sisällä. Kolmiulotteinen työskenteleminen kuvataiteessa [Inside and Around: Three-dimensional Practice in Visual Art]. Helsinki, Finland: Aalto Arts Books. Aalto University Publications, Doctoral Dissertations 143/2015.

Ojanen, S. 2016. The potential and limitations of re-using and recycling of construction products from the perspective of circular economy. Master's Thesis, Aalto University. <https://aaltodoc.aalto.fi/bitstream/handle/123456789/22169/master_Ojanen_Severi_2016.pdf?sequence=1> Accessed 30.11.2016.

Pajunen, N. 2015. Decision making towards sustainability in process industry – drivers, barriers and business opportunities. Doctoral dissertation. Aalto University. 978-952-60-6360-7 (electronic).

Pajunen, N. Mäkikoskela, R. 2016. Breaking out the silos - towards sustainable society – art, engineering and decision making perspectives (Part II). Keynote presentation. XXVIII International Mineral Processing Congress, September 11–15, Québec City, Canada.

Pajunen, N. Mäkikoskela, R. 2015. Breaking out the silos - towards sustainable society- art, engineering and environmental management perspectives (Part I). The 10th Conference on Sustainable Development of Energy, Water and Environment Systems, September 27 – October 2, Dubrovnik, Croatia.

Pajunen, N., Aarnio, T., Heiskanen, K., Watkins, G. (2015) Value in sustainability – the process industry perspective. International Journal of Sustainable Engineering. Online 4 August 2015. DOI: 10.1080/19397038.2015.1062936.

Pajunen, N., Rintala, L., Aromaa, J., Heiskanen, K. 2015. Recycling – the importance of understanding a complexity of the issue. International Journal of Sustainable Engineering. Online 25 August 2015. DOI:10.1080/19397038.2015.1069416.

HYBRIDS P3 Damage detection

Antin, K-N. Damage Detection in CFRP Components Using DIC. 2016. Advancement of Optical Methods in Experimental Mechanics 3, 57–62.

Näreikkö, A. 2015. Mechanical testing of unidirectional carbon fiber reinforced plastics. Master's thesis. Aalto University.

T. Siponkoski, M. Nelo, H. Jantunen, J. Juuti, The electromechanical properties of printable P(VDF-TrFE)-PZT composite with very high piezoelectric coefficient, Advanced Functional Materials (to be submitted).

T. Siponkoski, H. Jantunen, J. Juuti, Low temperature curable high performance piezoelectric ink for different substrates, Composites Science and Technology (to be submitted).

J. Tolvanen, J. Hannu, J. Juuti, H. Jantunen, LCP-PZT polymer composite strips for high temperature sensor applications, Electronic Materials Letters (to be submitted).

Vilmi, P, Sorvoja H. and Fabritius T. Printable autonomously working activity sensor with wireless data transmission. Scientific Report (to be submitted).

HYBRIDS P3 Noise and vibration

Antila, M. et al., 2015. Psychoacoustic Evaluation of Rock Crushing Plant Noise. In Proc. of Euronoise 2015.

Karhu, M., Lindroos, T. & Miettinen, A., 2015. Geometriapohjaisen ohjelmiston (GEODICT) mahdollisuudet ja soveltuvuus avosoluisen vaahtorakenteen akustisten ominaisuuksien ennustamiseen. In Akustiikkapäivät 2015. Kuopio: Akustinen seura ry, p. 7.

Tanttari, J. & Parviainen, H., 2015. Suodattavat rakenteet ja akustiset metamateriaalit. In Akustiikkapäivät 2015. Kuopio: Akustinen seura ry, p. 6.

HYBRIDS P3 Controlling the interfacial properties in hybrid materials

Palola, S., Sarlin, E., Kolahgar Azari, S., Koutsos, V. & Vuorinen J. 2017, Microwave induced hierarchical nanostructures on aramid fibers and their influence on adhesion properties in rubber matrix. Submitted to Applied Surface Science.

S. Palola, E. Sarlin, J. Vuorinen, Perspectives on the industrial implementation of novel microwave assisted surface modification method for aramid fibers. Journal of Advanced Materials (Accepted for publication 2017).

E. Sarlin, R. Sironen, T. Pärnänen, M. Lindgren, M. Kanerva, J. Vuorinen, The effect of matrix type on ageing of thick vinyl ester glass-fibre-reinforced laminates. Composite structures (Accepted for publication 2017).

M. Lindgren, S. Siljander, R. Suihkonen, P. Pohjanne, J. Vuorinen, Erosion-corrosion resistance of various stainless steel grades in high-temperature sulfuric acid solution. Wear, Vol. 364–365, 2016, 10–21.

R. Suihkonen, M. Lindgren, S. Siljander, E. Sarlin, J. Vuorinen, Erosion wear of vinylester matrix composites in aqueous and acidic environments at elevated temperatures. Wear, Vol. 358–359, 2016, 7–16.

R. Suihkonen, J. Perolainen, M. Lindgren, K. Valtonen, N. Ojala, E. Sarlin, J. Vuorinen, Erosion wear of glass fibre reinforced vinyl ester. Tribologia: Finnish Journal of Tribology, Vol. 33/2015, 11–19.

E. Sarlin, M. Lindgren, R. Suihkonen, S. Siljander, M. Kakkonen, J. Vuorinen, High-temperature slurry erosion of vinylester matrix composites – The effect of test parameters. Wear, 328–329, 2015, 488–497.

M. Lindgren, R. Suihkonen, J. Vuorinen, Erosion wear of various stainless steel grades used as impeller blade materials in high temperature aqueous slurry. Wear, Vol. 328–329, 2015, 381–400.

E. Sarlin, A. Rosling, M. Mustakangas, P. Laihonen, M. Lindgren, J. Vuorinen, Diffusion of acidic solution through rubber at high temperature and its effect on metal-rubber interface degradation. Proceedings of the SAMPE Europe Conference, Amiens, France, 14th–18th September 2015.

E. Sarlin, M. von Essen, M. Lingren, P. Kallio, J. Vuorinen, A novel micro-robotic approach to study the environmental degradation of matrix and fibre materials. Proceedings of the SAMPE Europe Conference, Liége, Belgium, 13th–15th September 2016.

E. Sarlin, M. von Essen, S. Palola, M. Lindgren, P. Kallio, J. Vuorinen, Determination of environmental degradation of matrix and fibre materials with a novel, statistically reliable micro-robotic approach. Proceedings of the 17th European Conference on Composite Materials, Munich, Germany, 26th – 30th June 2016.

Antti Ahvenainen: 3D Solid Modeling for Composite Pressure Vessels. Master's Thesis. Aalto University, 2017.

Juho Posio: Interlaminar shear strength testing of non-unidirectionally reinforced composites. Master's Thesis. Aalto University, 2016.

Meri Saarimäki: Kehittyneet palonkestävät komposiittirakenteet. Master's Thesis. Tampere University of Technology, 2017.

HYBRIDS P4 SP1 Oil free contacts for low and elevated temperatures: T1 sliding, T2 rolling and T3 flow contacts

Orell, O., Vuorinen, J., Jokinen, J, Kettunen, H., Hytönen, P., Turunen, J. & Kanerva, M.: Characterization of elastic constants of anisotropic composites in compression using digital image correlation, (submitted to Composite Structures)*

Mechanical characterization of laminates with micromechanical and numerical analysis comparison TUT & VTT (to be submitted)*

Rolling contact model including micro topography, VTT & TUT (to be submitted) *

Abrasive wear testing of polymeric materials, VTT

*All with Valmet Technologies

HYBRIDS P4 SP2: Lubricated sliding bearings and fixed connected surfaces – SLIBE

Orell, O. 2014. Polymer Liners in Journal Bearings – Literature Review, DIMECC Report, Tampere University of Technology.

Oksanen, V., Lehtovaara, A., Kallio, M. 2016.Load Capacity of Bismuth Bronze Bimetal Bearing in Lubricated Conditions, Proc. of 17th Nordic Symposium on Tribology, Aulanko, Finland, June 14–17. The updated paper has been submitted to Tribology International.

Linjamaa, A.2015. Modelling and Analysis of Elastic and Thermal Deformations of a Hydrodynamic Journal Bearing, MSc-Thesis, Tampere University of Technology.

Linjamaa & A. Lehtovaara, A. 2015. The Effect of Elastic and Thermal Deformations on Journal Bearing Performance, Presentation, 7th TWC International Conference, Tampere, Finland, Oct 28.

Linjamaa, A. Lehtovaara, A., Kallio, M., Söchting, S. 2015. Modelling and Analysis of Elastic and Thermal Deformations of a Hydrodynamic Radial Journal Bearing, Presentation, 24th Int. Baltic Conference in co-operation with IFHTSE, Engineering materials & Tribology, Tallinn, Estonia, Nov 5–6.

Linjamaa, A. Lehtovaara, A., Kallio, M., Söchting, S. 2016. Modelling and Analysis of Elastic and Thermal Deformations of a Hydrodynamic Radial Journal Bearing. Key Engineering Materials 674(2016), pp. 127–132.

Linjamaa, A., Lehtovaara, A., Kallio, M., Söchting, S. 2016. A. Modelling and Analysis of Elastic and Thermal Deformations of a Hybrid Radial Journal Bearing. Proc. of 17th Nordic Symposium on Tribology, Aulanko, Finland, June 14–17. The updated paper has been accepted to Tribology International.

HYBRIDS P5 Fundamentals and Modelling

Waudby R, Andersson P, Holmberg K, Low-speed sliding tests with nodular cast iron in contact with steel wire and a diamond tip, Tribology International 65 (2014) 171–176.

Holmberg K, Laukkanen A, Ronkainen H, Waudby R, Stachowiak G, Wolski M, Podsiadlo P, Gee M, Nunn J, Gachot C, Li L,Topographical orientation effects on friction and wear in sliding DLC and steel contacts, part 1: Experimental, Wear, Wear of Materials 2015 Special Edition, 2015, In press.

Waudby R, Varis T, Suhonen T, Holmberg K, Apostol M, Lindroos M & Kuokkala VT, Proceedings of the 5th World Tribology Congress, 8–13.9.13, Torino, Canada.

E. Isotahdon, E. Huttunen-Saarivirta, V.-T. Kuokkala & M. Paju: Corrosion behaviour of sintered Nd-Fe-B magnets Materials Chemistry and Physics 135 (2012) 762-771.

E. Isotahdon, E. Huttunen-Saarivirta, V.-T. Kuokkala, L. Frisk & M. Paju: Corrosion protection provided by electrolytic nickel and tin coatings for Nd-Fe-B magnets Journal of Alloys and Compounds 585 (2014) 203–213.

E. Isotahdon, E. Huttunen-Saarivirta, V.-T. Kuokkala & M. Paju: Corrosion mechanisms of sintered Nd-Fe-B magnets in the presence of water as vapour, pressurized vapour and liquid. Journal of Alloys and Compounds 626 (2015) 349–359.

E. Isotahdon, E. Huttunen-Saarivirta, V.-T. Kuokkala & M- Paju: Corrosion Losses in sintered (Nd,Dy)-Fe-B Magnets for Different Magnet Geometries. IEEE Magnetics Letters, 7(2015) no. 5500504.

E. Isotahdon, E. Huttunen-Saarivirta & V.-T. Kuokkala: Development of magnetic losses during accelerated corrosion tests for Nd-Fe-B magnets used in Permanent Magnet Generators. CORROSION 72(2016)6, pp. 732–741.

Linjamaa, A., Lehtovaara, A., Kallio, M. Söchting, S., Modelling and analysis of elastic and thermal deformations of a hydrodynamic radial journal bearing, Key Engineering Materials Vol. 674 (2016) pp 127–132.

Antin K-N, Harhanen L, Bossuyt S, Damage Detection In CFRP Components Using DIC, Advancement of Optical Methods in Experimental Mechanics 3(2015)57–62.

Antin K-N, Jalava K, Mechanical Properties of Cast Aluminium Matrix Composites Reinfroced with SiC and Al_2O_3 Particles, Proceeding of the International Conference on Composite Materials 20, July 2015, Copenhagen, Denmark, 4212–2.

Kiilakoski J, Lindroos M, Apostol M, Koivuluoto H, Kuokkala V-T, Vuoristo P, Characterization of High-Velocity Single Particle Impacts on Plasma-Sprayed Ceramic Coatings, Journal of Thermal Spray Technology 25(2016) 1127–1137

Kiilakoski J, Lutoschkin A, Plachetta M, Apostol M, Koivuluoto H, Killinger A, Vuoristo P, Fracture Characteristics of High-Velocity Suspension Flame-Sprayed Aluminum Oxide Coatings, International Thermal Spray Conference & Exposition 2016, 10.–12.5.2016, Shanghai, China, DVS Media GmbH, Germany, 466–471.

E. Isotahdon, E. Huttunen-Saarivirta & V.-T. Kuokkala: Characterization of the microstructure and corrosion performance of Ce-alloyed Nd-Fe-B magnets. Journal of Alloys and Compounds 692(2017) pp. 190–197.

J. Leppaniemi, J. Lyytinen, O. Elomaa, K. Suomalainen, J. Koskinen, The influence of PVD coatings on the wear performance of steel dental curettes, Key Eng. Mater. 674 (2016) 289–295.

J. Leppaniemi, P. Sippola, M. Broas, J. Aromaa, H. Lipsanen, J. Koskinen, Corrosion protection of steel with multilayer coatings: improving the sealing properties of Physical Vapor Deposition CrN coatings with Al_2O_3/TiO_2 Atomic Layer Deposition nanolaminates.

J. Leppaniemi, S. Hoshian, K. Suomalainen, T. Luoto, V. Jokinen, J. Koskinen, The influence of thin film coatings on non-stick properties of dental restorative instruments.

J. Leppaniemi, T. Sarikka, P. Sippola, H. Lipsanen, J. Koskinen, Adhesion and corrosion protection of Atomic Layer Deposited coatings on steel.

J. Leppaniemi, P. Sippola, J. Aromaa, H. Lipsanen, J. Koskinen, Effect of surface wear on corrosion protection properties of Physical Vapor Deposition CrN coatings with Al2O3/TiO2 Atomic Layer Deposition nanolaminates.

Palola, S., Sarlin, E., Koutsos, V., Vuorinen, J. Microwave induced hierarchical nanostructures on aramid fibers and their influence on adhesion properties in rubber matrix. Applied Surface Science (under review).

Palola, S., Sarlin, E., Vuorinen, J. Perspectives on the industrial implementation of novel microwave assisted surface modification method for aramid fibers. Journal of Advanced Materials, Special Edition 2017 (to be published).

Fantozzi D, Matikainen V, Uusitalo M, Koivuluoto H, Vuoristo P, Chlorine-induced high temperature corrosion of Inconel 625 sprayed coatings deposited with different thermal spray techniques, Surface & Coatings Technology 2017 (http://doi.org/10.1016/j.surfcoat.2016.12.086).

Korobov Y, Nevezhin S, Filippov M, Makarov M, Malygina I, (Ekaterinburg, Russia), Study of High Velocity Arc Sprayed heat resistant coatings from FeCrAlBY cored wire.

Fantozzi D, Milanti A, Koivuluoto H, Vuoristo P, (Tampere, Finland), proceedings of International Thermal Spray Conference, 10–12.5.2016, Beijing, China.

O. Orell, J. Vuorinen, J. Jokinen, M. Kanerva, H. Kettunen, P. Hytönen, J. Turunen, Qualitative and quantitative characterization of elastic constants of anisotropic polymer composites with digital image correlation, Composite Structures.

V. Matikainen, G. Bolelli, H. Koivuluoto, P. Sassatelli, L. Lusvarghi and P. Vuoristo, High-temperature sliding wear behaviour of thermally sprayed Cr_3C_2-based coatings, Proceedings of the 17th Nordic Symposium on Tribology Nordtrib2016, 14-17.6.2016, Hämeenlinna, Finland.

V. Matikainen, K. Khanlari, A. Milanti, H. Koivuluoto and P. Vuoristo, Spray parameter effect on HVAF sprayed (Fe,Cr)C-30FeNiCrSi hardmetal coatings, Thermal Spray 2016: Proceedings of the International Thermal Spray Conference, 10-12.5.2016, Shanghai, China, ASM International, 2016, pp. 184–189.

V. Matikainen, H. Koivuluoto and P. Vuoristo, Microstructural characteristics of different Cr_3C_2 coating compositions sprayed with HVAF process, Proceedings of the 28th International Conference on Surface Modification Technologies, 16-18.6.2014, Tampere, Finland, Valardocs, 2015, pp. 77–87.

V. Matikainen, G. Bolelli, H. Koivuluoto, P. Sassatelli, L. Lusvarghi, P. Vuoristo, Sliding wear behaviour of thermally sprayed Cr3C2-based coatings, Wear, 2017, (submitted).

V. Matikainen, G. Bolelli, H. Koivuluoto, M. Honkanen, M. Vippola, L. Lusvarghi and P. Vuoristo, A Study of Cr_3C_2-based HVOF and HVAF Sprayed Coatings: Microstructure and Carbide Retention, Journal of Thermal Spray Technology, 2017, (submitted).

Linjamaa, A., Lehtovaara, A., Larsson R., Kallio, M., Söchting, S., Modelling and analysis of elastic and thermal deformations of a hybrid journal bearing, Tribology International.

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ISBN 978-952-238-195-8
ISBN 978-952-238-196-5 (pdf)
DIMECC Publication series
ISSN 2342-2696 (online)

9 789522 381958