DIMECC

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BSA – Breakthrough Steels and Applications

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Wide and Deep Industrial Commitment Strengthen DIMECC's Forerunning Role in EU

During the last three years of DIMECC BSA, we have witnessed an extraordinary period in the Finnish R&D&I landscape. The development has been like a double-edged sword: on one hand, the European Commission and our cooperation partners all over the world have identified Finland as the European forerunner in the implementation of the public private partnership (PPP) model for digitalizing industry. On the other hand, challenges in the Finnish public economy have led us to a situation in which Finland is one of the few countries in the EU without an outspoken, industry-led, and publicly supported manufacturing industry digitalization strategy.

The DIMECC innovation platform, which is a form of networking, has enlarged, widened, and increased the impact and efficiency of collaboration between companies, universities, and research institutions. Since 2008, we have led industrial renewal and the dedicated manufacturing PPP platform in Finland. The results are significant: companies participating in our platform totally outperform outsiders. Global breakthrough concepts and innovations are reported in our programs on a continual basis. The DIMECC Breakthrough Materials Doctoral School, one of the most well-known BSA outcomes, is the largest and widest industrial doctoral school in Finland.

Many highlights of the BSA results are introduced in this final report. I would like to thank all the BSA actors for many years of strong cooperation, and for the dedicated use of everybody's time to create and develop the PPP model that we know today. In addition, many new co-creation services have been started based on the visionary needs identified through the implementation of BSA. As an example, I would like to mention our capability to influence standards in ship-building, regarding the acceptance of high-strength steels and lighter structures. The DIMECC program participants' systemic and integrative approach to changing businesses and energy efficiency is a natural continuation of our long-term and determined R&D&I facilitation, in which we boost cross-industrial innovation and lead industrial renewal.

The DIMECC co-creation platform makes a significant wave of innovation-based investment happen. This has been seen, for example, in Oulu, where many new metal industry digitalization start-ups have been born. This has also been seen in Hämeenlinna, where SSAB concentrates their production. We create competitiveness, jobs, and well-being through innovation. Technology Industries Finland announced on September 1st, 2016, that DIMECC is a platform for creating 100,000 new jobs in Finland.

Our role in the European innovation landscape and PPP pioneering has been recognized not only by our customers, but also by labor unions, by economists from many perspectives, and at the highest possible level: the EU Commission. Industry and the academic world have taken their responsibility for the structural renewal needed now in Finland. We created DIMECC Ltd. by merging Digile Ltd. into FIMECC Ltd. We have all the digital competencies, and an industry digitalization agenda ready to be executed.

Since the start of our company, metals and steel have been simultaneously a research object, a research context, and the basis for most of the other content taken forward within our community. I hope readers enjoy the versatile collection of results regarding the most important backbone of our daily lives: steel, which we all, in the western world, use every day more than bread.

Dr. **Harri Kulmala**
CEO, DIMECC Ltd.

Creating Cutting-edge Solutions and Capabilities for Industrial Success

The overall goal set for the DIMECC Breakthrough Steels and Applications (BSA) program is to enable a renewal of the Finnish engineering and ferrous metal industries through major improvements in their offerings and global competitiveness, brought about by the intelligent use of novel, advanced steel products in key applications.

The applications concerned are central to the Finnish engineering industry: 1) offshore and marine structures, 2) arctic structures, 3) equipment for power generation, 4) mining and mineral processing equipment, 5) lifting, handling, and transport equipment, 6) equipment for waste recycling, 7) bioenergy, and 8) equipment for the processing industry. Many of these areas have been identified as emerging technologies with a huge future business potential.

The program has tackled these goals by: a) building a solid basis for optimal, new-generation material solutions for emerging processes and applications, b) establishing the tools and design rules needed to utilize recent breakthrough steel developments in superior high-performance engineering products, c) developing completely new-generation steel and ferrous cast material concepts, with currently unavailable combinations of technological properties and life-cycle efficiency, that can serve as future product platforms, and d) developing and utilizing fundamental scientific knowledge together with multi-scale modeling and simulation tools to radically shorten the time to market for new customized steel products by digitalization of the R&D process for steel products and related material design.

BSA has made a major contribution to the effective DIMECC innovation ecosystem by building these capabilities and critical new solutions for industry. This includes close collaboration between companies from various parts of the steel value chain, research institutes, and universities, supported by extensive networking with international research partners. In addition to the major steel producers and steel-applying manufacturers, a number of small and medium-sized companies representing various fields and applications, as well as the key groups from several research organizations, have been strongly committed to the joint work, significantly expanding the possibilities for major change in the Finnish metal and mechanical engineering industry's structure and production capability. BSA, prepared and run in parallel with another DIMECC materials program, HYBRIDS (Hybrid Materials), has strengthened the strong and effective ecosystem with more than 60 companies dedicated to application and industry-driven materials R&D&I, and to digitalizing materials development.

A key success factor in solving the critical industrial research challenges through the latest scientific knowledge and tools has been creating an environment in which the key experts from different fields of industry and science meet and work consistently together. Systematic program preparation, focusing on real needs and identifying critical research problems and key players, was elemental. In addition, important technical developments, and especially the working mode and trust created between many core players in the previous program, FIMECC DEMAPP (2009–14), has given BSA a good basis and a fluent start.

One novel element, the DIMECC Breakthrough Materials Doctoral School, created for DIMECC BSA and HYBRIDS together, has proven to be a really important tool to complement the industry-driven projects in both programs. In this, we have built comprehensive world-class capabilities in so-called integrated computational materials engineering (ICME), boosting the implementation of modern experimental and multi-scale modeling tools to solve real industrial problems effectively. This digitalized materials development enables crucial shortening of the development time, in many cases to 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.

The DIMECC Breakthrough Materials Doctoral School, with its 38 doctoral students, is the biggest industry-led doctoral school in Finland. However, it is much more than that. In the unique working mode, doctoral researchers, working daily in the industry-led projects of the BSA and HYBRIDS programs, team up regularly with their peers through 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 multidisciplinary research entity, this group solves critical research challenges, defined together with industry, creating important, unique know-how and competence in modern, application-driven digital materials engineering. This is a significant asset for the DIMECC ecosystem and, more widely, for Finnish society.

The three large industry-led project entities of the BSA program have concentrated on creating new capabilities in chosen areas, based on specific industry needs. The first project has developed, for example, optimal corrosion- and high-temperature-resistant material solutions for new, emerging industrial processes and applications, such as renewable energy, bioprocesses, and water management. The second project has focused on comprehensive studies of the latest advanced high-strength and ultra-high-strength steels in the marine industry and machinery, by establishing a solid scientific and experimental basis, including fabrication, welding, fatigue, and long-term performance, to change the current design rules and enable practical implementation of highly energy- and material-efficient structures in these applications. The third project has developed novel, specialized, life-cycle-efficient breakthrough steel concepts and special cast materials for future applications. Great results have been achieved overall, from scientific novelties to market-ready products.

When starting the program, it was envisaged that, as a result of BSA, the Finnish engineering and ferrous metal industry would see a major change in its structure, with world-leading sought-after offerings in its product portfolios and new turnover amounting to 5 billion euros in 2020. I feel that the DIMECC BSA has already made a big, positive impact. In addition to a variety of novel solutions and capabilities developed for industry, the DIMECC ecosystem and platform has created a strong basis for making the next big things together. The final impact of BSA will, of course, be seen after a few years, but it also depends on the next actions. If the positive path can be continued, the Future will be bright!

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

Dr. **Markku Heino**
DIMECC BSA Program Manager
Senior consultant, Docent
Spinverse Ltd.

From Research to Solutions in Co-operation Network

The DIMECC BSA program has been a good continuation of earlier Demapp and Light programs. The research work around abrasion-resistant and ultra-high-strength steels has continued in 2014–2017. The optimization of process parameters and novel chemical compositions enable even more excellent combinations of mechanical properties, workshop usability, and better properties for end-users. In the development of novel high-strength steels, it is also very important to understand the customer needs. This project has provided a lot of new understanding of wear, manufacturing, and design matters. When the design-construction-maintenance-recycling cycle is considered as a whole, steel often offers the best properties.

The background to success has been the intensive co-operation, good basic research, and excellent togetherness of the members of DIMECC BSA. This way of working, started in earlier programs, has continued and showed its strength. For example, in the case of SSAB, the University of Oulu has made basic metallurgical research and SSAB has used these results in steel development. Excellent results with high industrial impact have been achieved over a wide range of hot-rolled products and applications. SSAB has developed several families of world-leading brands: in wear-resistant (Hardox) and ultra-high-strength steels (Strenx), and armor steels (Ramor), bringing energy-efficient, light solutions for transport, as well as safety and new performance in wear and protection applications. Other companies, like Metso and Meyer, have continued from this to develop their own applications.

Even though the project was shorter than planned, we have got very good results. Now it is important for everybody to go through all the results carefully, both in the projects they have been directly involved with and across the entire program. In this way, the given expectations and promises of the program can be fully redeemed. As a result of the DIMECC BSA program, we will see an extended lifespan of machinery and cost savings in various structural components. We will see it in the form of a decreasing ecological footprint and in the increasing competitiveness of Finland in the changing markets of the world.

I wish to thank all of you who have worked on the program, and I hope that this work continues in the future in new developing programs.

Pertti Mikkonen
Product Development Manager,
Hot-rolled products,
SSAB Europe Oy

DIMECC BSA – The Best Form of Cooperation for the Steel Research Alliance

Metals are ideal materials to help meet our society's growing needs for infrastructure in a sustainable way. Not only are they affordable and readily available, but their intrinsic properties, such as high strength, possibility of microstructural engineering, excellent workability, versatility in processing and use, durability in service, and possibility for 100% recycling, allow for improved environmental performance throughout the entire life-cycle of buildings. The most important metals are clearly steels. Steels are part of our daily lives and our future, and they have strongly influenced our history. The European Coal and Steel Community was created after the Second World War to support cooperation between nations. This community was the first step toward the European Union. Steels are part of art and architecture (buildings and infrastructure), and they are used in transporting people and goods, in machines, and in the production and transport of energy, food, water, and chemicals.

The need to combat climate change means that by 2030, the use of fossil energy in Europe has to be reduced by 30% and primary raw materials by 20%, which together will result in a 40% reduction in CO_2-equivalent footprints. The use of high-strength steels will be crucial in solving this massive challenge.

The DIMECC BSA program brought together a wide variety of companies and universities working on steel science and engineering. The main idea of DIMECC BSA is to focus on new business areas, enhancing knowledge of steel applications and boosting business using the R&D network. The tool of this is tight cooperation between industry and research organizations, so that industry leads the projects and research centers focus on strategic research. Hence, researchers from Aalto University, HAMK University of Applied of Science, Lappeenranta University of Technology, Metropolia University of Applied of Science, Tampere University of Technology, VTT, and the University of Oulu work together with people in 31 different companies. This is absolutely one of a kind worldwide.

It is clear that the DIMECC BSA program has given a long-term perspective and continuity to academic research, helping universities to develop and ensure research quality through the production of publications and doctoral degrees. This work has been done together with industry partners, and the research work can be shown to be successful.

I would like to thank Tekes for the public funding and DIMECC for the excellent management that made the high-level research possible.

Jukka Kömi
Professor, Physical Metallurgy,
Head of Materials and Production Engineering Unit,
Faculty of Technology, University of Oulu

DIMECC BSA
Program Key Characteristics

Company partners (Pcs.): 30

Research institute partners (Pcs.): 7

Volumes:

Duration: .... 1.1.2014 – 30.6.2017

Budget: .... 25 M€

Company budget: .... 13 M€

Research institute budget: .... 12 M€

People involved: 120

Results:

Number of publications: 246

Number of doctoral theses: .... 7 (+ 20 on-going after the program ends)

Number of other theses: 41

Patents and invention disclosures: 2

Research exchange months: 43.6

Volume of spin-off projects........ 20 M€ planned & prepared

Enabled business potential (estimate):........ 4 billion €

A? Aalto University School of Engineering
ANDRITZ
arctech WE MAKE YOU BREAK THE ICE
ATA GEARS
AURAJOKI OY
NEW BOLIDEN
COMPONENTA
CORESTO
DELTAMARIN
Fortum
FOSTER WHEELER
HAMK HÄMEEN AMMATTIKORKEAKOULU UNIVERSITY OF APPLIED SCIENCES
KONECRANES Lifting Businesses
KUORMAVÄLINE OY
Open your mind. LUT. Lappeenranta University of Technology
Majava
Marioff United Technologies
Metropolia
metso
MEYER TURKU
moventas GEARED FOR NEW ENERGY
NESTE OIL
UNIVERSITY of OULU OULUN YLIOPISTO
outokumpu
Outotec
OVAKO
PONSSE
POSIVA
PROTOLAB
RUUKKI
SAVCOR
SSAB
TAMPERE UNIVERSITY OF TECHNOLOGY
TVO
VTT
WÄRTSILÄ
ÄÄNEVOIMA OY

Muottikarkaistavien teräslaatujen kehityslinjat

Käyttövarmuutta kattiloihin uusilla materiaalivaihtoehdoilla

Tuntemalla olosuhteet voit optimoida materiaalit kulutussovelluksiin

Terrific ferritics: rising costsdrive innovation

Valumateriaalit ja valmistusmenetelmät kehittyvät

HITSAUS TEKNIIKKA

1/2017

3M Science. Applied to Life.

Suomen kilpailuvalttina

Uudet materiaalit ja pinnoitteet

Digitaalinen materiaalikehitys luo säästöä ja tehokkuutta teollisuuden materiaaliratkaisuihin

Protolab otti julman ilmeen

Metallin tutkimus tehostuu

Protolabin miehistönkuljetusajoneuvo

- PMPV 6X6 "MiSu" on parempaa suojausta ja lisää liikkuvuutta tutkimuksella ja tuotekehityksellä -

Telakkateollisuuden suomalaismullistus: Lujempi teräs mahdollistaa uuden hyttikannen

Luja teräs – iso laiva

Hammaspyörät kestävämmiksi ja laakerit liukkaammiksi

Ultralujien terästen ominaisuudet lopputuotteeseen osaavan suunnittelun ja valmistuksen avulla

Savcor sai uutta tietoa korroosiosta

Hissi kevenee kitkaa parantamalla

Korkean lämpötilan materiaalit energiateollisuudessa:
Uudet tuulet ja eliniän hallinta

Tutkimus maksaa itsensä takaisin

Ramor 450 provides the best vehicle blast protection on the market

Todellisuutta simuloiva kulumistestaus on haastavaa, mutta hyödyllistä

Materiaalitekniikkaan iso tohtoriohjelma

Materiaalitekniikka siivittää tuulivoimavaihteiston kilpailukykyä

Materiaaleja haastaviin kulumisolosuhteisiin

Tuotannon digitalisointi etenee materiaaleihin

Mari Lindgren/Outotec (Finland) Oy
Pekka Pohjanne/VTT Technical Research Centre of Finland Ltd

Crevice corrosion of cost-efficient stainless steels: experimental observations, online monitoring on pilot scale, and computational modeling

Summary of the project's motivation and achievements

The project developed integrated methods and tools to estimate the materials performance and remaining lifetime of stainless steel structures and components in the metallurgical and pulp and paper industries, where corrosion resistance is the key question. This was achieved by an improved understanding of degradation mechanisms and the development of techniques to predict and manage corrosion phenomena. The project was focused on complex corrosion modes that are difficult to simulate on laboratory scale and in which the combination of experimental testing and modeling can provide significant added value. Particular focus was given to crevice corrosion under deposits of cost-efficient stainless steels, which is currently poorly understood but important due to the prevalent presence of various scales and deposits in the process industry.

Crevice corrosion tackled through integration of:

- laboratory-scale corrosion studies to understand the role of deposits in localized corrosion in aggressive environments and to generate data for modeling
- pilot-scale tests coupled with online monitoring under conditions corresponding to those in the process of interest to provide validation data
- computational modeling using the coupled environmental model

Increased lifetime and safety by taking control of crevice corrosion phenomena.

The experimental work concentrated on the stainless steel grades EN 1.4404 (316L), EN 1.4539 (904L), EN 1.4462 (2205), and EN 1.4410 (2507), but other passivating alloys, such as EN 1.4521 (444), 654SMO, Hastelloy C-2000, and pure titanium (grade 2), were also investigated for comparison. The morphology and extent of crevice corrosion is influenced by a number of variables: the test material and its surface characteristics, the composition of the bulk solution, and the type and dimensions of the crevice. Plenty of valuable new information was obtained to enable cost-effective alloy selection for the demanding process conditions of the metallurgical industry. Novel online monitoring sensors were developed to detect crevice corrosion; these find applications in a wide variety of industries and sectors, and facilitate the early detection of materials degradation. The developed multi-physics model is based on both corrosion theories and experimental kinetic data, and is capable of predicting the time evolution of several key parameters: conditions within the crevice and progress of damage within the material. The project proved that experimental work and computational modeling support each other seamlessly and, when combined, bring phenomenological understanding to a new, higher level. Such understanding can be applied in predicting the behavior of materials in complex hydrometallurgical processes and in estimating the remaining life of the components.

Key results and impacts

Laboratory studies on the corrosion mechanisms

Experimental work was conducted in order to understand the influence of experimental variables on the occurrence and extent of crevice corrosion, to improve knowledge of the role of deposits, and to support modeling. This contained failure analyses on samples collected from the field, immersion tests, and laboratory experiments using, for example, spring-loaded crevice formers. Examinations of samples collected from the field revealed heterogeneous deposits from the process, in addition to localized and general corrosion, severe erosion, and cavitation. The direct connection between the presence of deposits and the occurrence of crevice corrosion could not therefore be established. In immersion tests, the severity of corrosion attack did depend not only on the chemical composition of the different stainless steel grades studied, but also on the metallurgical properties of the test materials.

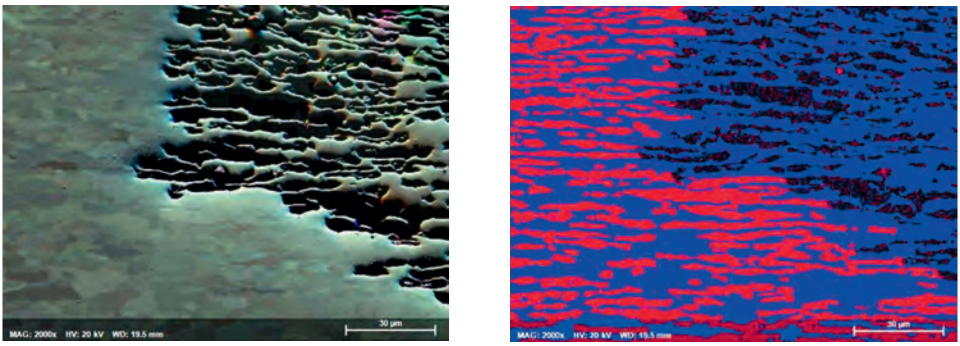
Chemical composition and phase structure dictate corrosion resistance.

Company impact

"The results will guide the alloy selection for conditions involving crevices that cannot be avoided."

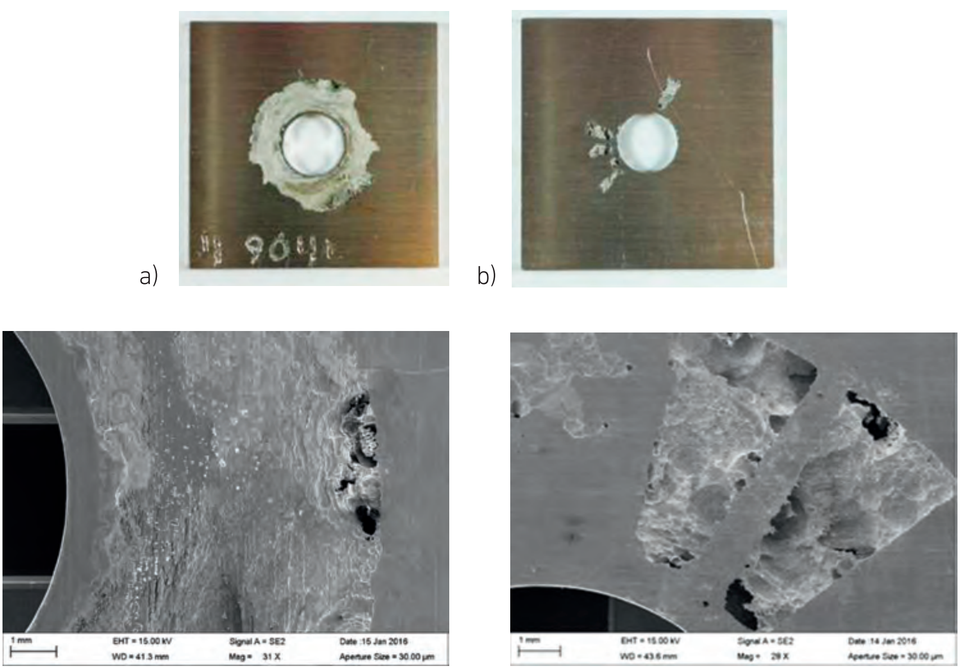
***Thomas Ohligschläger,** senior research engineer at Outokumpu*

Differences in the morphology of corrosion attack related to the chemical composition of the studied stainless steels were observed. For example, in the test environments containing 10 g/l H_2SO_4, 10 g/l Fe^{3+} and varying amounts of Cu and Cl^-, the damage had penetrated deeper in austenitic grade EN 1.4539 (904L) than in duplex grades EN 1.4462 (2205) and EN 1.4410 (2507). In the case of duplex stainless steels, selective dissolution of the phases was also detected, with austenite typically being the phase that underwent dissolution (Figure 1). Detailed analyses confirmed the concentration of crevice attack in the vicinity of the crevice former's liquid side edge. The extent of damage was also dependent on the type of crevice former (Figure 2).



a) b)

Figure 1. SEM/EBSD analyses of the mechanism of crevice corrosion in EN 1.4462 (2205) duplex stainless steel, grooved crevice former. Test solution: 50 g/l H_2SO_4, 1000 mg/l Cl^-, and Fe^{3+}= 0,5 g/l. Austenite phase = red, ferrite phase = blue



c) d)

Figure 2. Photographs (a, b) and SEM images (c, d) showing differences in the nature and extent of crevice corrosion between the types of crevice formers: a, c) smooth surface; b, d) grooved surface. Alloy: EN 1.4539 (904L); test solution: 50 g/l H_2SO_4, 1000 mg/l Cl^-, 0.5 g/l Fe^{3+}

Experimental polarization curves were determined for several stainless steel grades, to provide input data for modeling and to understand the influence of environmental conditions and alloy composition on the materials behavior. The main endeavor was to understand the role of various oxidizing agents, meaning the potential, in crevice corrosion to provide a phenomenologically based model for complex cases. To get high-quality input data, for example, the influence of Cl^- content (Figure 3) and of stainless steel grade were determined. Repassivation behavior was approached using scratch tests, which disclosed differences in the repassivation kinetics between the alloys. Repassivation capability is vital for proper performance under the combined action of corrosion and wear, so these results are of great importance for materials selection for, for example, hydrometallurgical applications.

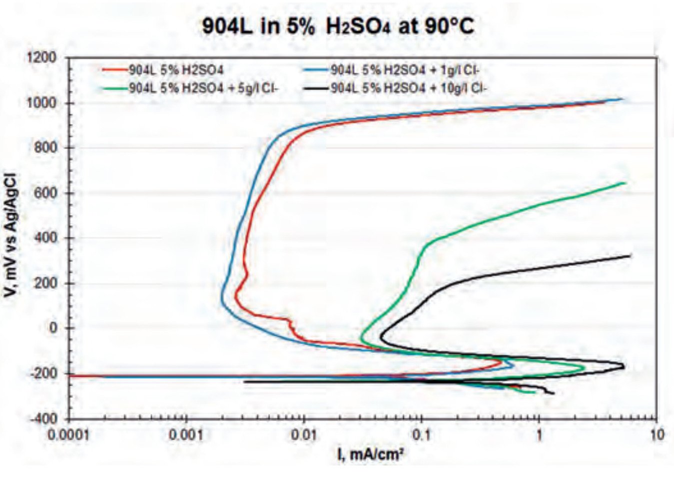


Figure 3. Polarization curves for EN 1.4539 (904L) in 5% H_2SO_4 at 90 °C as a function of Cl^- content

Pilot-scale tests coupled with online monitoring

Pilot-scale crevice corrosion monitoring was conducted for various instances with a different focus. A new sensor (Figure 4a) was developed that enabled the determination of the open-circuit potential in a crevice. The performance of the new sensor was evaluated in conjunction with two continuous process pilots (Figs. 4b and c) with the duration of several weeks, and the obtained data was correlated with the process parameters. The first process pilot investigated the performance of three grades of stainless steel: EN 1.4539 (904L), EN 1.4462 (2205), and EN 1.4410 (2507). In one reactor, the sensor measured the open circuit potential (OCP) of material surfaces, while in another reactor, OCP was recorded in the crevice. The tests were operated under very severe con-

Hybrid electrochemical sensor enable crevice corrosion risk monitoring.

ditions: acidic, oxidizing and elevated temperatures, and high amounts of chlorides. In the batch-wise tests, Cl^- was added stepwise in the system. The results revealed that the chloride additions were reflected in the trends in the measured OCP values in both reactors. The monitoring results also disclosed that the OCP within the crevice was systematically lower than that on free surfaces (Figure 4d). The second pilot included an OCP sensor and a crevice OCP sensor of the alloy EN 1.4462 (2205), and the redox potential of the process solution was also monitored. The OCP in the crevice correlated well with the redox potential in the crevice and, for example, the Fe^{3+} content of the process solution (Figure 4e). In addition, the OCP in the crevice was consistently lower than the OCP on a free surface, with greater scatter in the values also being detected. After the tests, the presence of crevice corrosion was confirmed by SEM examinations. The overall conclusion is that the developed sensors operated as planned, and provided valuable evidence of lower potential within the crevice than on free surfaces.

Company impact

"In future, the sensors may be applied in a range of industrial sectors to monitor the possibility for crevice corrosion."

***Isto Virtanen**, supply and aftersales manager, Savcor Oy*

In addition to the continuous process pilots, batch-wise simulations were employed to verify the performance of the sensor and to generate validation data for modeling.

Computational modeling

The aim was to develop a model for under-deposit crevice corrosion that has a firm scientific basis, is robust to use in practice, determines when corrosion is likely to occur and what the maximum penetration depth is, and gives the relationship between the operating environment and the propagation of corrosion. The model is based on a commercial finite-element software package (COMSOL). The computational domain consists of the electrolyte, and both the crevice former and the corroding material are modeled as boundary conditions. In the electrolyte, mass and charge transfer, electrical potential distribution, and electrolyte chemistry are solved. For modeling the reaction kinetics of the corroding material, experimental data is required as an input. The model can provide data on surface reactions, electrochemical changes within the electrolyte, and geometry changes of the crevice as a function of time. The time evolution of conditions within the crevice (Figure 5) provides important information regarding, for example, passivity breakdown and progress of active corrosion.

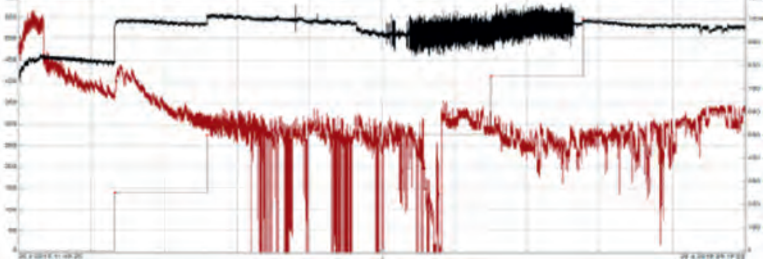
Modeling brings phenomenological understanding to a new level.

Company impact

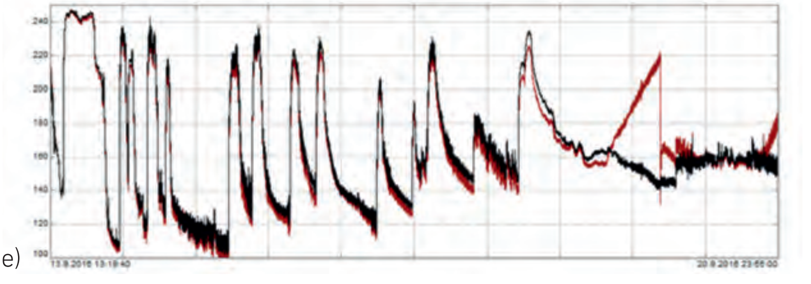
> "The crevice corrosion modeling tool makes it possible to predict material performance in order to aid cost-effective materials selection for complex applications and to reduce time-to-market of new products."
>
> ***Mari Lindgren,** development manager at Outotec*

It will be first implemented in operational environments relevant to hydrometallurgical leaching processes, but the tool is based on a modular structure, so it is expected to be applicable to other industrial systems, as well.

a)  b)  c) 

d) 

Black – OCP of the free surface *Red – OCP in the crevice*
Thin step-wise progress in red – redox potential of the solution

e) 

Black – OCP in the crevice *Red – Redox in the crevice*

Figure 4. **a) Developed sensors. Reactors used in the first (b) and second (c) process pilot. Examples of the curves collected for 2205 (EN 1.4462) in the first (d) and second (e) process pilot**

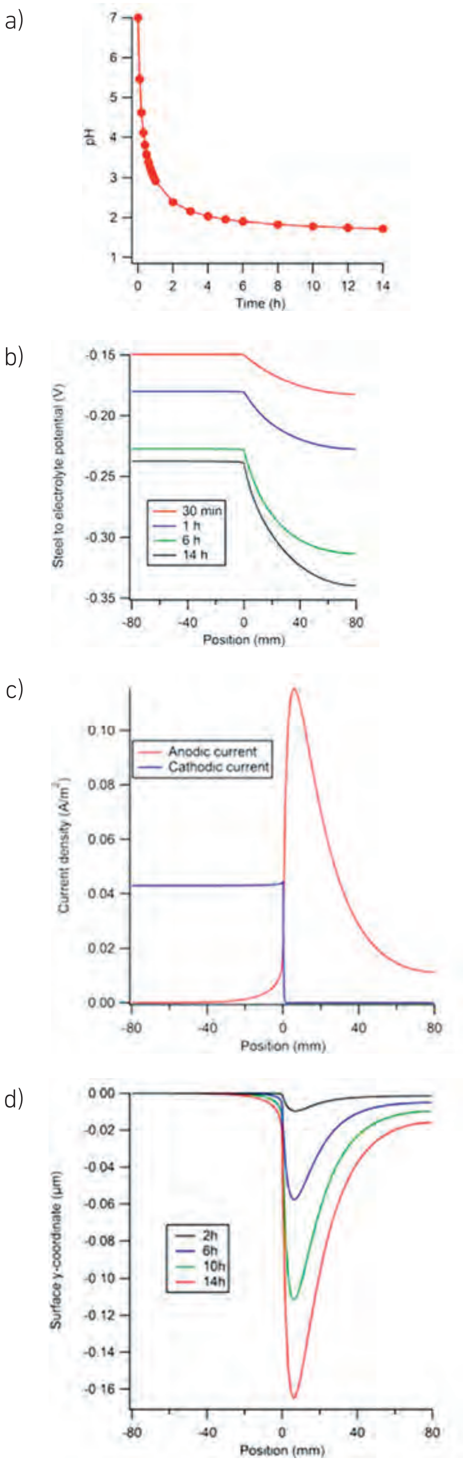


Figure 5. **Time evolution of conditions in the crevice for EN 1.4301 (304) steel in neutral salt water (pH=7, 0.6 M NaCl); a) pH, b) potential, c) current density, d) penetration depth and location**

Further information

KEY PUBLICATIONS:

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

Lindgren, M., Siljander, S., Suihkonen, R., Pohjanne, P., Vuorinen, J. Erosion-corrosion resistance of various stainless steel grades in high-temperature sulfuric acid solution, Presentation in NordTrib 2016 symposium 6/2016.

Aronen, J., Influence of chemical composition on crevice corrosion of some ferritic stainless steels, MSc thesis in Outokumpu, 2015.

Raunio M., Basic approaches and goals for crevice corrosion modelling, RESEARCH REPORT VTT-R-02078-15, 2015.

Raunio M., Properties and monitoring of precipitates and related corrosion, RESEARCH REPORT VTT-R-02118-15, 2015. (together with BSA/P1SP3-DETER)

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Edgardo Coda/Amec Foster Wheeler Energia Oy
Satu Tuurna/VTT Technical Research Centre of Finland Ltd

Lifecycle efficient material solutions for power production – Productive boiler

Summary of the project's motivation and achievements

The pressure to maintain fuel flexibility, meaning also an increased use of economical, low-quality fuels with high efficiency, has resulted in a severe fouling and corrosion challenge for fireside surfaces in boilers and other high-temperature process piping. New changing process conditions also have an effect on microstructural alloy stability during long-term performance in processes at high service temperatures. Certification from material suppliers or simplified laboratory testing is not sufficient proof to qualify a material whose unexpected failure may cause major economic losses or personal accidents. Long-term testing in commercially operating units constitutes the backbone of materials qualification for these challenging applications.

During the project, a separated pressure loop was successfully installed in the Äänevoima power plant to enable long-term testing of materials in real operational conditions. The loop enables testing of different steam data, also covering future plants, without interfering with the steam production of the hosting commercial unit. The results of tests give us information on material behavior in both the fireside and the steam side of the tubes. Exposed materials included different steel tube materials and also some weld overlay coatings. The first set of samples has been removed and characterized, and testing will continue at least until summer 2017.

Instrumentation and control systems become increasingly important when higher capacity, efficiency, and cyclic operation, together with reliability, are targeted. An online electrochemical probe/sensor is one way to monitor changes in operational conditions, such as in fuel, deposit formation, and temperature. The mechanical durability of sensors can be a challenge in demanding service environments, in order to achieve a long enough testing period to collect sufficient material performance information from real service. The campaigns in different service environments have been carried out during the project. The positioning of the sensor during the campaign affects the obtained results and their usability.

One key target was to find out the most critical and the remaining lifetime-limiting factors regarding furnace tubes. Samples from Neste furnaces were removed for remaining-lifetime investigations. The studies revealed the most relevant failure modes. Together with the right inspection procedures, the optimal moment for furnace tube changes can be determined.

Key results and impacts

Novel weld overlay coatings provide cost efficiency and high performance.

In applications requiring good oxidation/corrosion resistance and creep resistance, such as in energy production and chemical processing environments, austenitic stainless steels and Fe(Ni)-base alloys have been used widely due to their heat/oxidation resistance. As the energy production and processing environments and increases in process temperatures are becoming more severe due to attempts to increase efficiency, the traditionally used materials are no longer able to withstand the processes. In order to keep up with the harsher environments and higher process temperatures, one way has been to develop Al-alloyed austenitic and ferritic stainless steels. In these steels, Al replaces part of the Cr and its high temperature oxidation resistance in combination with good creep resistance is achieved at a lower alloying cost than, for example, with Ni-base alloys. Aalto University and VTT did laboratory-scale exposure tests for weld overlays with screening purposes for coming field testing, and also to define the main corrosion mechanisms. As a result of the elevated temperature exposure, at temperatures of 550–950°C, it was observed that sufficient Al-alloying (≥ appr. 3.5 wt-%) resulted in the formation of protective slowly growing Al-oxide on the surfaces. This oxide produced excellent oxidation resistance, which was better than for the more expensive Ni-base superalloy and traditionally used AISI 347 HFG austenitic stainless steel (Figure 1). Similarly, Si-alloying improves early-stage elevated temperature oxidation resistance in stainless steels. Si-alloying promoted oxidation resistance, which was almost at the same level as Al-alloyed stainless steels. In Al-alloyed materials, such as Ni-base superalloy Inconel 52, with insufficient Al-alloying (<3.5 wt–%), formation of the protective Al-oxide layer on the surfaces of the materials was not obtained, and the materials suffered from internal oxidation, degrading their high temperature performance (Sarikka 2017). In a simulated biofuel environment at 550°C, containing sulfides and chlorides, the Al-alloyed stainless steels performed well with corrosion/oxidation resistance far better than the traditionally used AISI 347 HFG austenitic stainless steel, which suffered from severe corrosion (out of scale in Figure 2).

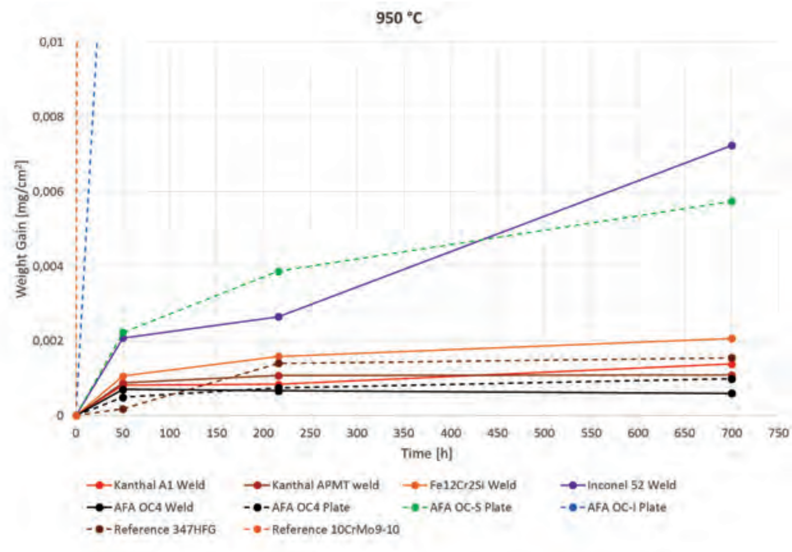

Figure 1. Weight gain/surface area of the studied materials at 950°C up to 700 h

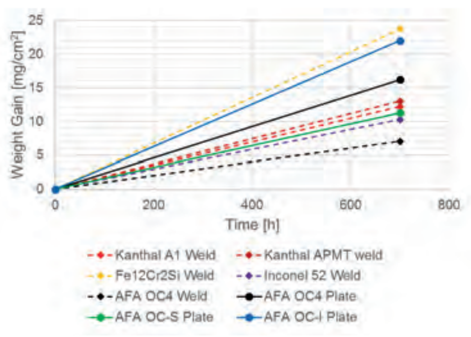

Figure 2. Weight gain for the studied materials subjected to 200 ppm SO_2–2000 ppm HCl – 15% water vapor – synthetic air (10% O_2–N_2) and 50 % KCl – 50% K_2SO_4 deposit for 700 h at 550 °C

Based on the results obtained in the laboratory-level tests at elevated temperatures, overlay weld tube component samples were prepared and installed in the steam loop at the Äänevoima plant (Figure 3). The overlay weld materials include previously used Kanthal A1, expensive Inconel 52 Ni-base superalloy, and Al-alloyed austenitic stainless steel AFA OC-4 (welding wire received from ORNL, USA).

"As service conditions in combustion processes become more aggressive due to increasing service temperatures and wider fuel variety, the interest in overlay welds increases, not only for repair purposes but also in the case of new installations," says Tony Puikkonen, Material Specialist at Andritz. Good bond integrity and thermal conductivity, as well as corrosion resistance, are desirable characteristics of overlays to provide an optimal lifetime for the coated components. An alternative solution for manufacturing components subjected to extreme conditions was developed, and the expected benefits of the manufactured overlay welds, and especially Al-alloyed austenitic stainless steel, are clear: increased lifetime, and operational reliability bringing longer operational periods without maintenance breaks and reductions in operational costs. The service exposure testing will continue with weld overlay samples, and Andritz will test the best-performing weld overlays manufactured by Aalto during spring 2017.

Figure 3. **FB boiler at the Äänevoima plant and an example of an overlay weld sample tube placed in the steam loop**

The designed and built steam loop in the Äänekoski FB boiler (Figure 3), for long-term material testing by Foster Wheeler Energy and Metsä Group, is a unique testing facility in Finland. The system consists of two separate loops, one running with a constant load and one with a cyclic load. The first tests were initiated in summer 2015, and the first removal of samples was done in May 2016 after 7600 hours of exposure. The test coil operating in cyclic mode unfortunately failed just before the outage, in April 2016. The exposure temperatures have been approximately 540°C and 570°C. The first obtained results were quite well in line with the laboratory test results. Higher Cr content (from 18% up to 26%) in the

Full-scale field testing is the key to understanding the complex environment to guarantee reliable solutions.

alloy leads to lower oxidation rates (Figure 4). The effect of surface cold work on the oxidation rate was also verified in the field test. Introducing cold work in the surface layer creates more paths for Cr to diffuse to the surface and form a protective oxide scale. All the samples that had a cold-worked inner surface showed very low oxide scale thickness values (micrometers only). The exposure continues, and the plan is to take the next samples out in the coming summer outage in 2017.

Company impact

"The material testing in actual operating conditions in the steam loop is important, as in laboratory experiments it is not possible to simulate all process parameters affecting oxidation and/or corrosion. The ability to define the temperature limits that steam side oxidation sets in real conditions for the boiler materials will enable us to design and fabricate more reliably supercritical and ultrasupercritical boilers."

***Jouni Mahanen,** R&D Engineer, Amec FWE*

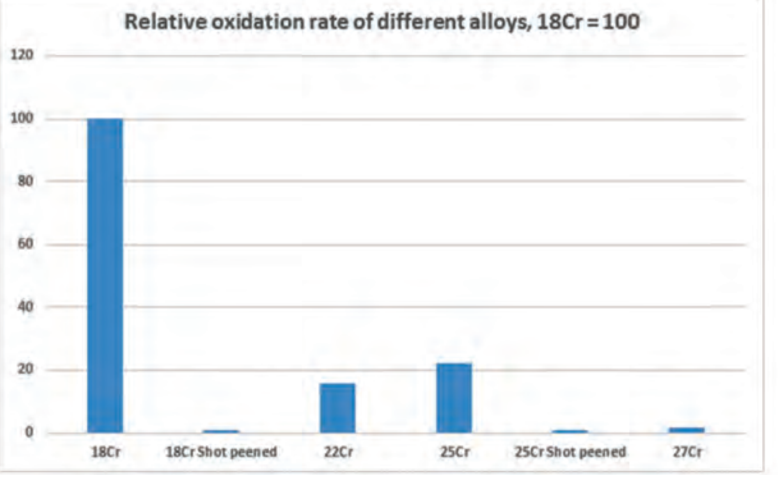

Figure 4. **Relative oxidation rate of materials tested in the steam loop for a year. The results normalized and compared to 18Cr steel**

Coresto and Andritz together carried out the first 1000 hours of the test campaign in spring 2015 with an online electrochemical probe in the Äänekoski black liquor recovery boiler, which is also a mechanically demanding environment for a probe. In addition to the resulting corrosion information, it was shown that the developed sensor lasted well in the demanding conditions of the recovery boiler. However, special attention must be paid to the positioning of the sensors; the sturdy mechanical structure of the sensor is not enough.

Coresto carried out the second electrochemical measurement campaign in January–February 2017, which was also done in the Äänekoski black liquor recovery boiler. The first measurement campaign focused mainly on testing the strength of the sensor, and this campaign was done at a constant temperature. In this second campaign, Coresto further tested the probe's mechanical structure, but also investigated 10CrMo material corrosion resistance at various temperatures. A temperature versus corrosion test was carried out using a 3G remote connection to set temperature set-point parameters. The measurement data was collected remotely, similarly to the first test. The developed sensor lasted mechanically well in this second ~800 hours measurement campaign, too. Figure 5 and Figure 6 present the results of the second campaign. It should be noted in the final analysis that all changes in the process must always be taken into account. For example, when changing temperature settings, there are also many other factors that can have an influence on corrosion at the same time. At least factors such as the boiler load, the type of fuel to be burned, the amount of air, and soot blowing must be taken into account when drawing the final conclusions from the results. In this connection, the results are presented without the consideration of the foregoing.

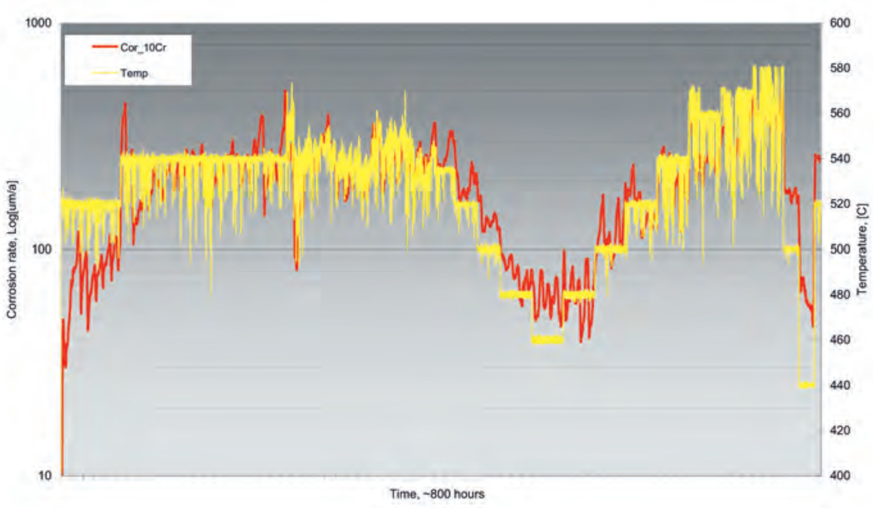

Figure 5. Material 10CrMo corrosion rate at various temperatures (440–580°C) during the test period

Measurement campaigns carried out in the project indicate that the redeveloped Coresto sensor and measurement system is also ideally suited for continuous monitoring of recovery boiler corrosion. It can be used to monitor changes in the recovery boiler, as well as, for example, to determine the critical temperature of the material.

Company impact

> "Systematic corrosion monitoring provides a cost-effective way to improve the reliability of critical components by obtaining info for remaining life assessment and aging management, plant uptime, and increasing overall business profitability."
>
> *Kari Kärkkäinen, CEO, Coresto*

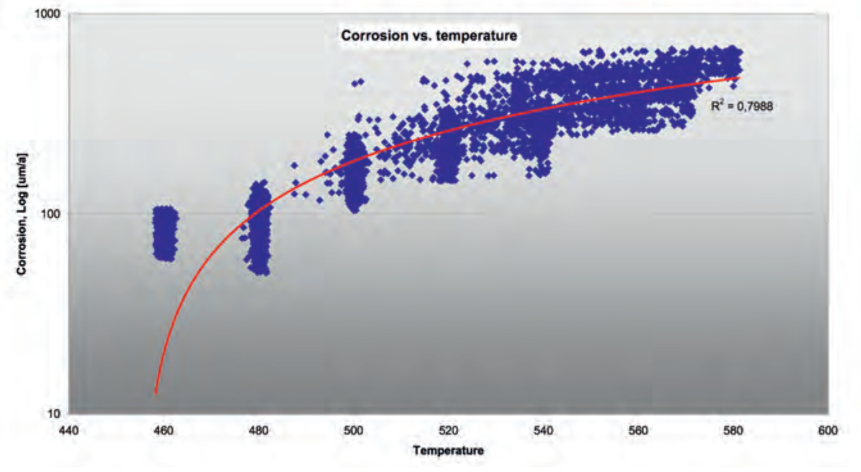

Figure 6. Material 10CrMo corrosion rate versus temperature presented without consideration of process changes

VTT has carried out miniature probe tests on a laboratory scale for corrosion online monitoring with 10CrMo and TP347HFG materials. The probe consisted of LPR- and EFM methods to verify the applicability of different methods for corrosion rate measurements. The combination of different methods turned out to be very challenging, and additional tests are required to troubleshoot clear dependencies between oxidation, corrosion, and different material types during measurement.

VTT also undertook one corrosion probe campaign in the Laanila eco power plant to test the functioning of a temperature gradient probe. This type of probe set-up can be used to define the critical temperature ranges of a certain material, for example during the planning of foreseen changes in operational parameters. A temperature-controlled, air-cooled probe was placed in the superheater area. Figure 7 shows the average temperature profile of the probe's sample section during the test and changes visible on the test material. The temperature gradient over the length of the sample area varied between 420–470°C. Pitting type corrosion was visible at the cooler end of the sample tube. With increasing temperature, corrosion accelerated and the surface of the test material showed a more uneven surface profile. The wall thickness measurements also showed the accelerated corrosion; the average wall thickness decreases with increasing temperature.

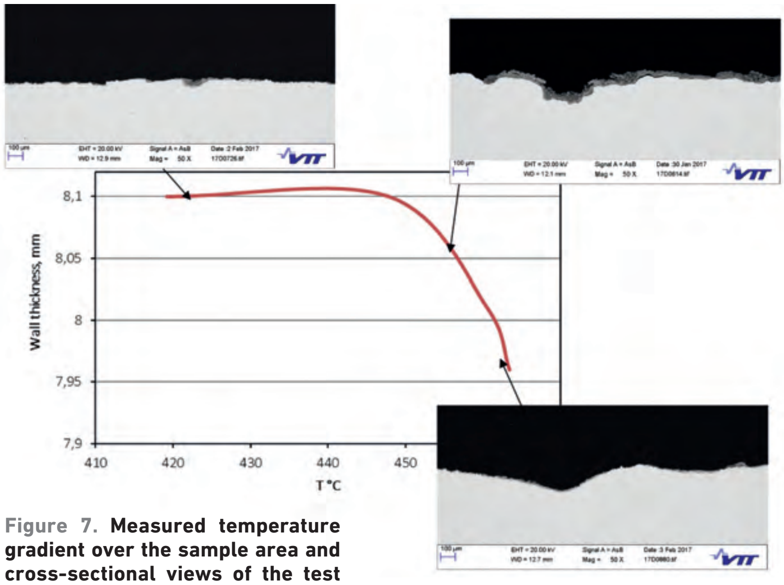

Figure 7. Measured temperature gradient over the sample area and cross-sectional views of the test material at different temperatures

The furnace tube failures are usually related to operational disturbances like overheating due to internal coking or local hotspots in the furnace. Together with the material temperature, the wall thickness of the tube plays an important role in limiting the remaining lifetime. The tube sample investigations confirmed this theoretical finding. The microstructures of the sample tubes after long high-temperature use reveal the degradation (Figure 8 and Figure 9). In addition, hardness decreased. Both are typical signs of long-term high-temperature use.

Characterization and testing give more precise information for further use.

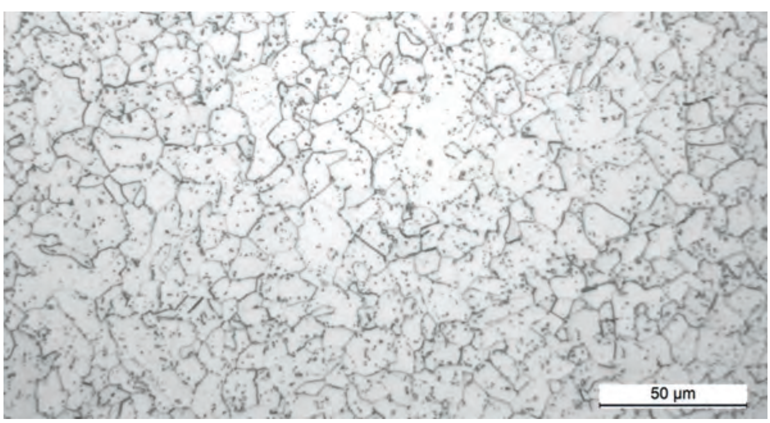

Figure 8. Microstructure of the tube, material P5 after 360 000 h operation, design temperature 560°C

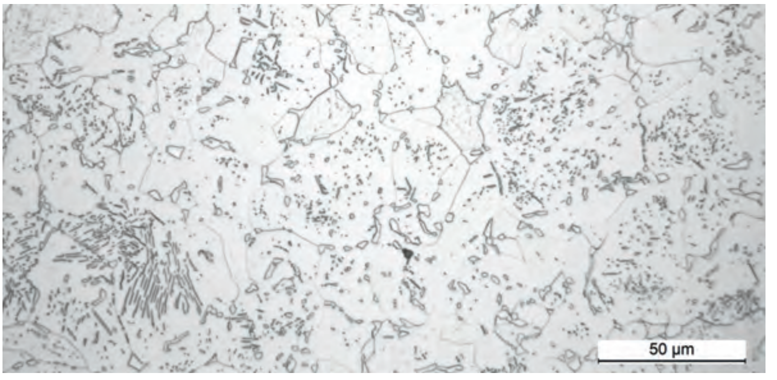

Figure 9. Microstructure of the tube, material P5 after 485 000 h operation, design temperature 475°C

Not all the creep tests are finished yet. However, it is already possible to conclude that even if the microstructure of the tube material shows degradation due to long-term high-temperature use, creep strength is still sufficient for further use, but only if the material temperature is controlled. In the remaining lifetime studies, it can be clearly seen that even a slight overheat can dramatically shorten the remaining lifetime. Overheating accelerates corrosion and accelerates the thinning of the tube wall, as well. Therefore, the most critical factors to be controlled in the furnaces are material temperature and wall thickness. Figure 10 presents the creep test results for the tube corresponding to the structure in Figure 8, and Figure 11 shows the results for the tube corresponding to the structure in Figure 9. With more alloyed tube materials, like austenitic stainless steels and nickel alloys, other microstructural factors should be taken into account, as well. These factors include brittle phase formations during the long-term high-temperature use, like intermetallics for example in the sigma phase. These studies were not carried out in this project, but these findings will be adopted in the inspection procedures.

Internal coking of the tubes is a problem because it raises the material temperature. Complete internal cleaning by pigging is going to be adopted as a standard maintenance procedure. Pigging will be carried out as a so-called smart pigging method, in which the wall thickness is measured at the same time. Wall thickness for each tube in the whole furnace is then measured, instead of spot measurements. Skin temperature measurements of furnace tubes will be installed more often, especially when renewing tubes/furnaces. More attention will be paid to operation at too high a tube temperature. Hot spots in the furnaces will be recognized. Replica inspections have also been introduced as a routine inspection method with furnace tubes. All these above-mentioned actions significantly improve the reliability and the safety of furnaces, since the critical life-limiting factors are known and better controlled.

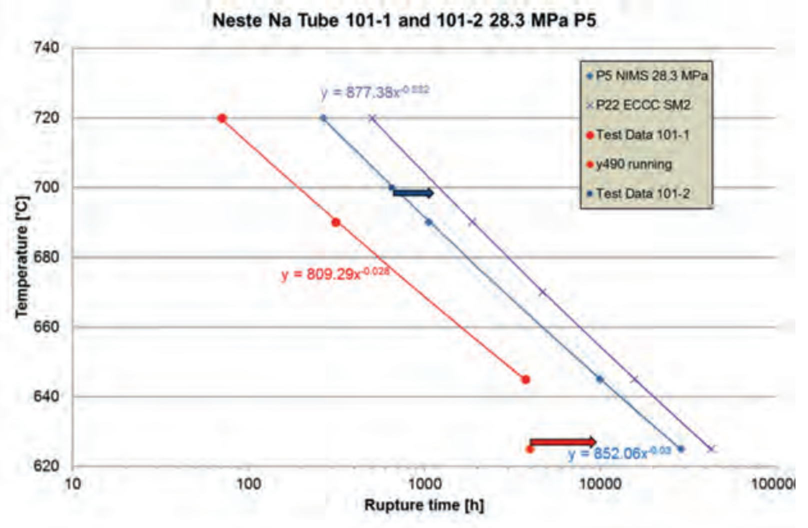

Figure 10. **Creep test results for tube material P5, after 360 000 h operation**

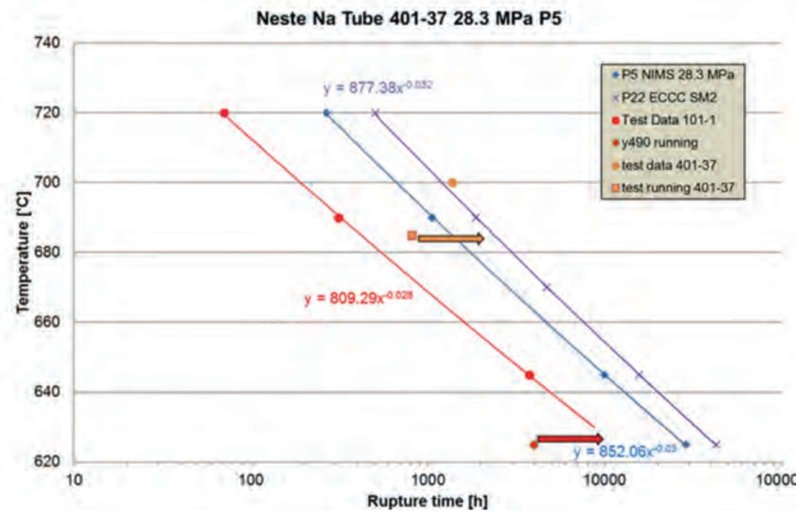

Figure 11. **Creep test results for tube material P5, after 485 000 h operation**

Company impact

"The results of the project are very useful and can be directly adopted in maintenance procedures. The most critical factors for limiting the remaining lifetime have been recognized. The findings have been brought into maintenance routines in practice. The criteria for changing tubes are also better understood: it is a combination of wall thickness and microstructural changes, where the wall thickness plays an important role."

Sari Musch, material and inspection specialist at Neste

Summary The project developed tools to estimate material performance and the remaining lifetime of components in demanding process conditions of future boilers by improving understanding of oxidation/corrosion mechanisms and by developing techniques to measure and predict corrosion phenomena. Instrumentation and control systems become increasingly important when higher capacity, efficiency, and reliability are targeted. The novelty value of the project includes the material performance information from combined laboratory and real service environments, utilizing corrosion probe measurements and long-term field testing. This is to facilitate the introduction of more efficient carbon-neutral combustion processes in real industry.

Collaborative action

AFA OC-4 welding wire and wrought AFA alloys for the tests were received from the Oak Ridge National Laboratory (ORNL), USA. The Massachusetts Institute of Technology (MIT), USA, delivered Fe12Cr2Si welding wire for the tests. The Laboratory of Inorganic Chemistry, Helsinki University, performed the XRD analyses of the test materials.

Further information

KEY PUBLICATIONS:

Sarikka, T., Romu J. & Hänninen, H. Early-stage oxidation behavior of Al- and Si-alloyed stainless steels as well as Ni-based alloy in air at elevated temperatures, to be published

Sarikka, T., Romu J., Hänninen, H., Tuurna, S. & Pohjanne, P. Performance of FeCrAl/Si- and Ni-based alloys in simulated biofuel environment, to be published

Pitkänen, V. 2014, Failure Mechanisms of Furnace Tube Materials in Porvoo Oil Refinery, Master's thesis

Yli-Olli, S., Auerkari, P., Tuurna, S., Pohja, R. & Holmström, S. 2016. Lifetime assessment: Modelling of Steamside Oxidation, Baltica X International Conference on Life Management and Maintenance for Power Plants.

Tuurna, S., Romu, J., Hänninen, H., Mahanen, J. & Puikkonen, T. 2017. Käyttövarmuutta kattiloihin uusilla materiaalivaihtoehdoilla, Hitsaustekniikka 1/2017.

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Leena Carpén/VTT Technical Research Centre of Finland Ltd

Mechanisms, monitoring and prevention of fouling and corrosion in industrial water systems

Summary of the project's motivation and achievements

Understanding mechanisms behind deposition, corrosion, and fouling in flowing and stagnant conditions is critical in providing reliable cooling and fire-water systems.

The project aims to deepen the understanding of the mechanisms behind deposition, corrosion, and fouling in cooling water cycles and in stagnant conditions in fire-water systems, leading to the development of improved monitoring and prevention technologies. The project has worldwide significance and the potential to generate new global industrial service products.

Cooling water systems are used to remove heat from components and industrial equipment. Water cooling is typically used for cooling large industrial facilities, such as power plants and chemical factories. The excess heat is transferred to cooling water in condensing systems. Many cooling water systems use natural waters. Due to moderate temperatures, cooling water cycles are susceptible to biofouling, inorganic fouling, and scaling, which may reduce heat transfer and enhance corrosion.

During this project, fouling and scaling and their effects on material and weld performance were studied in two power plants and one steel mill, as well as under simulated laboratory conditions. Our results enlighten the mechanisms of early settlement of biofouling and the consequence of biofouling on material performance.

Formerly, many fire-water mains were made of carbon steel or cast iron. At present, stainless steel is adopted in fire-water piping and is also a material for sprinkler and spray heads, where typically copper alloys have been and are utilized. Stainless steels usually have good corrosion resistance in cold, flowing, clean, and low-chloride water. However, in stagnant water, such as that typically found in fire-water systems, corrosion resistance evidently diminishes. Stagnant water conditions and only intermittent operations after often long stagnant periods also pose their own special demands for chemical treatments.

Our common deliverable was to have a basic understanding of the mechanisms of deposit forming in water systems, as well as of the effects of water quality on corrosion in fire-extinguishing systems.

Key results and impacts

The results obtained using the pilot-scale cooling water circuit (Figure 1) showed that there were differences between the six stainless steel grades in terms of tendency toward biofouling and corrosion. The two alloys that were most abundant with respect to biofouling were austenitic grades AISI 316L and AISI 316plus, while the surfaces of ferritic grade AISI 444 contained the least bacteria and archaea. The duplex grade featured signs of localized corrosion after the tests, but localized corrosion was minor. Biofouling made the alloys AISI 304L, AISI 316L, and LDX2101 more susceptible to pitting corrosion, but this requires the potential values, meaning the oxidizing capacity of the environment, to be increased by, for example, the addition of disinfection chemicals. Particularly in the case of AISI 304L and AISI 316L, the duration of the experiment during which pitting corrosion susceptibility was increased was only 8 weeks. Therefore, it is possible that in longer-term exposures, these materials may become susceptible to localized corrosion even without the external increase in the oxidizing capacity, if the trends detected by cyclic anodic polarization measurements continue. The obtained results may have implications in the materials selection for cooling water systems employing brackish water from Baltic Sea, because it is much more practical to use proper alloys that do not facilitate biofilm formation than to add chemicals to combat them.

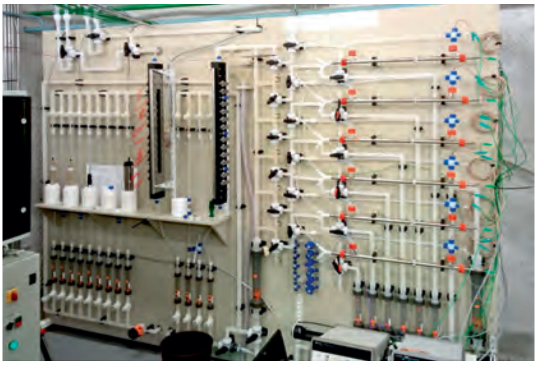

Figure 1. Pilot-scale cooling water circuit at VTT

Welds

Welds in cooling water systems are frequent, with welding being one of the key methods of joining pipes, tubes, and system components together. However, welds may pose challenges to system performance, because they protrude from otherwise smooth surfaces, they often have a rougher finish than the surrounding areas, and the metallurgy may deviate from that elsewhere in the structure. Therefore, the way the welds behave in the cooling water systems is of great interest in this project. To obtain improved understanding of corrosion and biofouling in cooling water system welds, two failure cases from different sites, located in the weld area, were examined. In the case of the power plant, the weld failure was detected in the welds of SMO254 (Figure 2a). The case from the steel mill cooling water system involved AISI 316 as a pipe material. In the first case, samples were taken from the cooling water, the biofilms that were developed on the surfaces of the pipes, and the failed pipes around the failure area (Figure 2b). The cooling water contained plenty of bacteria, and particularly sulfate-reducing bacteria (SRB). The quantity of microbes on the surfaces varied from place to place. The highest bacteria count was detected in the weld sample, but not all welds involved bacteria. In addition, the overall quantity of SRB was high. Detailed characterization of bacterial groups demonstrated the presence of alphaproteobacteria, such as manganese-oxidizing bacteria (MOB) and iron-oxidizing bacteria (IOB). The corrosion products on the material surfaces contained plenty of manganese. The obtained preliminary results suggest that the weld failure in 254SMO was because of microbially induced corrosion. This is a unique finding, because the alloy is considered to perform well in systems involving brackish water.

Weld defects cause a higher risk of microbially induced corrosion.

In the steel mill, leaks were discovered in a pipe system containing process water made up of natural water. A detailed examination of the corrosion damage revealed a clear relation of the leaks to weld defects and to the retained heat tints inside the tubes.

Company impact

"Improved monitoring and prevention technologies can be developed and used in these systems with the help of these results."

***Ritva Korhonen,** senior engineer at Fortum*

"In order to be able to specify the right material and proper welding procedures in the future not only in our plant but also at our customers' sites, it is essential for us to understand the interactions between the stainless steel, the weld oxides and the natural water that caused the corrosion damages."

***Thomas Ohligschläger,** senior research engineer at Outokumpu*

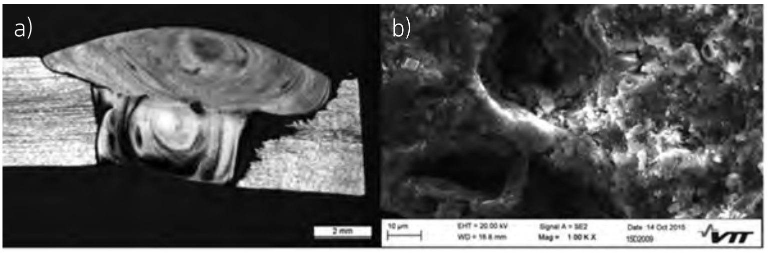

Figure 2. Photographs showing the failed weld.
a) Optical microscope image of the weld in etched condition;
b) SEM image, showing microbes around the failed weld

Biofouling control

Chemical cleaning of the fouling affected area is the main method used for removing unwanted biofouling in the cooling water systems. Currently the most common biocide to prevent biofouling in once-through cooling systems is hypochlorite. In addition to biocides, biofouling may be prevented by application of coatings developed to prevent the settlement of fouling organisms. Coatings also allow the use of less corrosion resistant metals such as carbon steel, since the base material is not in direct contact with water. In this research, we examined biofouling and materials degradation in a brackish seawater environment using a range of test materials, both uncoated and coated.

The susceptibility to fouling of several materials, and the effectivity of chlorination in fouling prevention, was studied in a power plant cooling water system. As in most cases in a natural water environment, the fouling consisted of both inorganic fouling and biofouling. Biofilm formation in the non-chlorinated system was intensive, but fouling also took place in the chlorinated system, where a biofilm consisting of bacteria, archaea, fungi, algae, and protozoa was detected. Chlorination reduced microfouling in brackish water by 10–1000-fold, but also altered the structure of the remaining community forming the biofilm on surfaces (Figure 3). Chlorination did not prevent the adhesion, but rather killed the biofouling species after attachment. In addition, the choice of material had an effect on the biofouling community in the beginning, but a prolonged exposure time unified the composition of the biofouling community between different materials (Figure 3). Multiple potentially corrosion-inducing species, such as manganese-oxidizing, sulfate-reducing, and iron-oxidizing bacteria, were detected on the surfaces of all materials. Chlorination also changed the composition of inorganic scaling. In addition to having a reducing and species-selecting influence on biofilm formation, chlorination also deteriorated the epoxy coating already during one month of exposure. On the other hand, coating combined with chlorination further reduced the microfouling on the surfaces compared to metallic surfaces.

An electrochemical measurement system designed for real-time monitoring of corrosion and fouling.

Based on the immersion experiment, an electrochemical measurement system was designed to monitor both corrosion and fouling in a chlorinated environment, enabling a real-time survey of surface conditions.

Company impact

> "This will help to monitor materials performance in cooling water systems."
>
> *Mikko Tausa, process engineer at TVO*

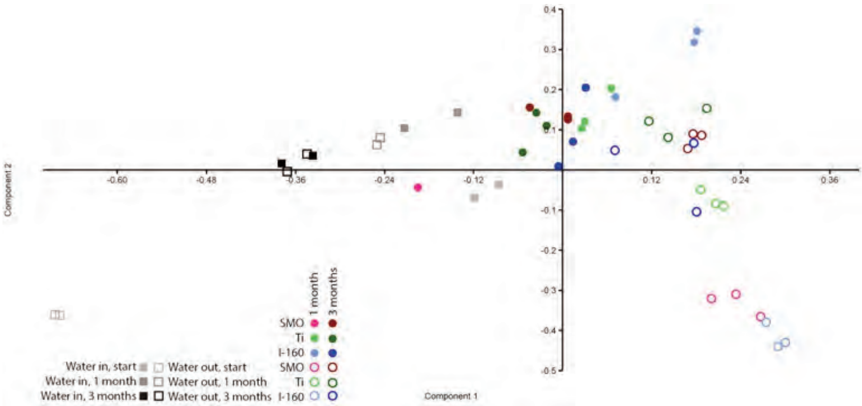

Figure 3. **Principal component analysis (PCA) plot showing the clear division of a bacterial community into chlorinated and non-chlorinated types. Open symbols indicate chlorinated and solid symbols non-chlorinated samples. Component 1 explains 39.2% and Component 2 26.2% of the variance, with actinobacteria, chloroplasts, alphaproteobacteria, and epsilonproteobacteria dominating the axis loadings**

The effects of biofouling and scaling on steels

Biofouling on and corrosion behavior of stainless steels AISI 304L (EN 1.4307), AISI 316L (EN 1.4404), 316plus (EN 1.4420), 254 SMO (EN 1.4547), AISI 444 (EN 1.4521), and LDX2101 (EN 1.4162) were investigated in a pilot-scale cooling water circuit using brackish water from the Baltic sea. Experiments were designed to last for a time period ranging from 8 to 18 weeks, that is, as long as differences in the behavior between materials could be distinguished. All materials showed a tendency to ennoblement in the cooling water environment, likely due to the biofilm formation on the surfaces. A heterogeneous biofilm, containing bacteria, fungi, algae, and protozoa, was found on the surfaces of all studied stainless steel grades. Nevertheless, there were differences between the test materials with respect to the extent of biofouling on the surfaces. In the first cooling water experiment, conducted for 8 weeks for the materials AISI 304L, AISI 316L, and 254SMO, the surfaces of grade AISI316L contained the highest amount of bacteria and archaea at the end of the test, with the lowest amounts being true for AISI 304L. In the second test, carried out for 17 weeks for grades AISI 444, AISI 316plus, and LDX2101, grade AISI316plus featured the highest amount of bacteria and archaea on the surfaces, whereas the lowest counts were realized for the ferritic grade AISI 444.

Materials showed improved resistance to corrosion with longer immersion times, as revealed by the results from the EIS measurements. This may be a result of thickening of the passive film, development of the (protective) biofilm, or a combination of these. However, the results demonstrate the evolution of the biofilms on the surfaces in all cases, necessitating that they contributed to detected changes in the surface behavior. Cyclic anodic polarization curves for three grades of stainless steels (AISI 304L, AISI 316L, and LDX2101) disclosed the possibility of pitting corrosion under highly oxidizing conditions, whereas those for the remaining three grades (AISI 444, AISI316plus, and 254 SMO) did not reveal susceptibility to pitting corrosion in the used brackish sea water.

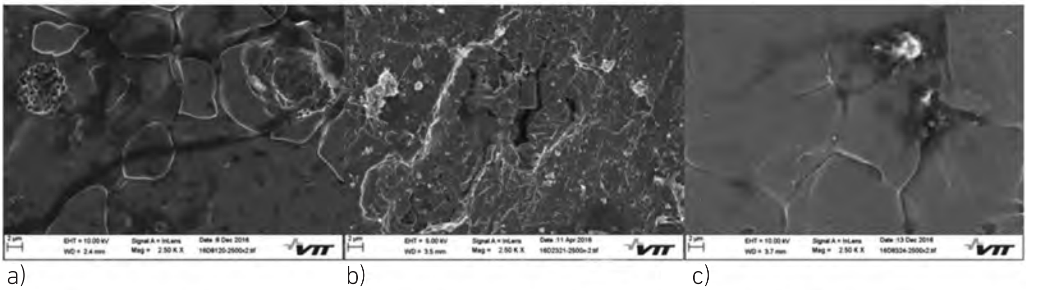
a) b) c)

Figure 4. SEM images showing surfaces of: a) AISI 316L, b) LDX2101, and c) 254SMO. Localized corrosion and biofilm may be detected in a) and b), while c) manifests only the presence of a biofilm

Under the OCP conditions of the cooling water circuit, localized corrosion was detected only in the cases of alloys AISI 316L and LDX2101 (Figs. 4a and b). However, a detailed examination of the unexposed test material showed that some of the marks interpreted as minor localized corrosion could actually be signs from the processing of the surface finish. It is emphasized that the tendency to pitting corrosion for the three materials AISI 304L, AISI 316L, and LDX2101 may cause problems if oxidizers such as sodium hypochlorite are added to the system, for example for disinfection. However, the duration of this study was only 8 weeks, so it is possible that in longer-term exposures, these materials may become susceptible to localized corrosion even without the externally added oxidizer.

Unique pilot cooling water circuit was implemented for biofouling and scaling studies. The results showed that the surface phenomena on stainless steels were similar to those occurring in the real industrial water systems. This is important finding because the phenomena are complex and typically difficult to simulate in laboratory conditions.

Fire protection water systems

In fire-protection water systems, stagnant water conditions prevail and the piping system has various small isolated areas and possible crevice sites. At present, the limits for suitable water quality to be used in fire-protection water systems are narrow in order to guarantee material performance in the systems. However, not all water that is available for filling the system fulfills these criteria. In this project, the effect of water parameters on crevice and general corrosion were studied, aiming to increase the field lifetime of components, at the same time as loosening the water quality requirements and providing customer savings in operational costs. The performance of alternative materials was also studied in various conditions.

In the first part of the study, a Master´s thesis comprising electrochemical measurements and long-term immersion tests of materials reflecting the present and potential future states in fire-protection components (including brass and austenitic, ferritic, and duplex stainless steels) was implemented. In addition, a crevice corrosion study of three stainless steel grades was conducted. Later in the program, another long-term immersion test was conducted in order to study a number of potential future states that were generated based on interpretation of the initial results, in addition to several reference environments.

All three test series gave comparable results for various stainless steel grades in corrosive water environments (Figure 5). The results are very useful for future material selection purposes in this field of technology, since they support the introduction of duplex and ferritic stainless steels to these applications, where austenitic steels cannot be used in all components due to their tendency toward stress corrosion cracking. The results also support the introduction of corrosion inhibition chemicals to these systems. The results can eventually lead to the replacement of certain legacy materials with certain stainless steels grades, which offer better overall corrosion resistance in demanding environments and thus increased reliability and a longer lifetime.

Duplex and austenitic stainless steels with proper corrosion inhibitor dosing.

The applicability of commercial corrosion inhibitors was studied in the context of these materials and application-based environments during the two long-term immersion tests. The latter test was conducted to verify the behavior of the second commercial inhibitor, in connection with dosing equipment designed for the application. Testing of the corrosion inhibition chemical and dosing equipment were conducted on a system scale. Based on these studies, the selection of a suitable corrosion inhibitor, as well as suitable dosing equipment for the application, can be implemented, providing a longer lifetime for materials in demanding environments.

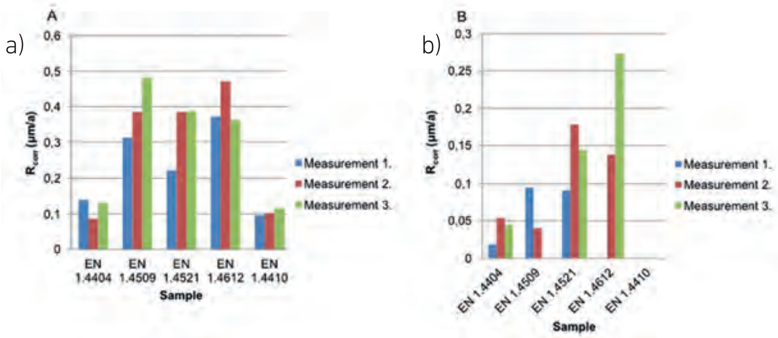

Figure 5. Corrosion rates for studied stainless steel grades under stagnant water conditions. a) Water with high oxygen content and high conductivity (Water 3); b) Water with high conductivity (Water 4)

Further information

KEY PUBLICATIONS:

Rajala, P., Sohlberg, E., Priha, O., Tsitko, I., Väisänen, H., Tausa, M., Carpén, L. Biofouling on Coated Carbon Steel in Cooling Water Cycles Using Brackish Seawater. J. Mar. Sci. Eng. 2016, 4, 74.

Rajala, P., Bomberg, M., Huttunen-Saarivirta, E., Priha, O., Tausa, M., Carpén, L. Influence of Chlorination and Choice of Materials on Fouling in Cooling Water System under Brackish Seawater Conditions. Materials 2016, 9, 475.

Rajala, Pauliina, Raunio, Maija, Sohlberg, Elina, Priha, Outi, Carpén, Leena. 2015. The effect of chlorination on microbially induced corrosion of carbon steel in cooling water system under brackish seawater conditions. 16th Nordic Corrosion Congress, NCC 2015, 20–22 May 2015, Stavanger, Norway. Proceedings.

Raunio M, Rajala P, Carpén L, Huttunen-Saarivirta E. Biofouling and corrosion on stainless steels in Baltic sea water environment: a cooling water pilot study, Baltica X conference 2016. Life Management and Maintenance for Power Plants, 7–9 June 2016, Helsinki-Stockholm-Helsinki. In: Baltica X. VTT Technology: 261, VTT, 17 p.

Raunio, M. Properties and monitoring of organic and inorganic precipitates and related corrosion. Research Report VTT-R-02118–15.

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DESIGN BEYOND CURRENT CODES

P2
SP1

Jani Romanoff, Heikki Remes/Aalto University

Competitiveness for the marine industry by superior design and manufacturing processes for high-performing steels

Background

Competitiveness through efficient use of materials

In 2013, the Association of Finnish Maritime Industries (AFMI) published a strategic research agenda to improve the competitiveness of the industry (see Figure 1). The agenda recognized the need to develop efficient structural solutions for specific application cases. The application cases were from different product segments, such as cruise ships and ferries, Arctic vessels, and offshore.

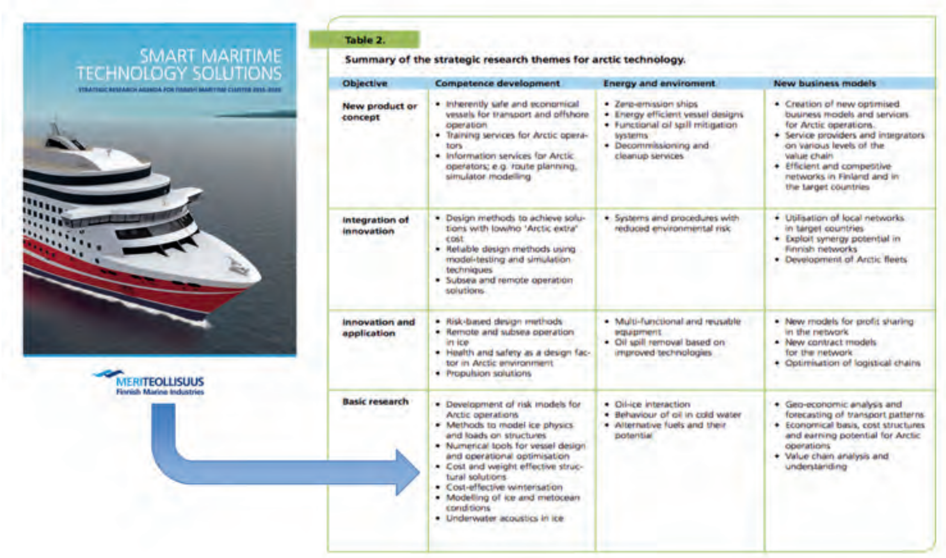

Table 2.

Summary of the strategic research themes for arctic technology.

Objective	Competence development	Energy and enviroment	New business models
New product or concept	• Inherently safe and economical vessels for transport and offshore operation • Training services for Arctic operators • Information services for Arctic operators; e.g. route planning, simulator modelling	• Zero-emission ships • Energy efficient vessel designs • Functional oil spill mitigation systems • Decommissioning and cleanup services	• Creation of new optimised business models and services for Arctic operations. • Service providers and integrators on various levels of the value chain • Efficient and competitive networks in Finland and in the target countries
Integration of innovation	• Design methods to achieve solutions with low/no 'Arctic extra' cost • Reliable design methods using model-testing and simulation techniques • Subsea and remote operation solutions	• Systems and procedures with reduced environmental risk	• Utilisation of local networks in target countries • Exploit synergy potential in Finnish networks • Development of Arctic fleets
Innovation and application	• Risk-based design methods • Remote and subsea operation in ice • Health and safety as a design factor in Arctic environment • Propulsion solutions	• Multi-functional and reusable equipment • Oil spill removal based on improved technologies	• New models for profit sharing in the network • New contract models for the network • Optimisation of logistical chains
Basic research	• Development of risk models for Arctic operations • Methods to model ice physics and loads on structures • Numerical tools for vessel design and operational optimisation • Cost and weight effective structural solutions • Cost-effective winterisation • Modelling of ice and metocean conditions • Underwater acoustics in ice	• Oil-ice interaction • Behaviour of oil in cold water • Alternative fuels and their potential	• Geo-economic analysis and forecasting of transport patterns • Economical basis, cost structures and earning potential for Arctic operations • Value chain analysis and understanding

Figure 1. **The need for lightweight solutions in marine and offshore applications (AFMI, 2013)**

When the design-construction-maintenance-recycling cycle is considered as a whole, steel often offers the optimal properties.

When **competitive products** are built, the key issue is to look at the **design-construction-maintenance-recycling cycle** as a whole. When this is done in a balanced way, ***steel often becomes the only material*** that can offer the best combination of properties. However, the **potential** of steel is **not fully utilized in the marine and offshore sector**. During the start of this project, major classification societies recognized materials with a yield point up to 390MPa in their rules. Moreover, fatigue strength, often being the bottleneck of design, was assumed to be equal regardless of the yield strength of the base material. Many national and EU-level projects had indicated that this is a far too conservative approach for design. In order to convince the authorities, two sub-projects were established, namely HIGHMARINE and EXTREMEST. While HIGHMARINE focused on cruise ships and Arctic vessels, the EXTREMEST project focused on offshore applications.

Solution

Basic research from the needs of application cases

In ship design, the design basis is a targeted operational life of 20-50 years. Typically, the hull of the ship is composed of bulkheads and decks. These are stiffened plate structures. Bulkheads carry the global, hull-girder shear loads and the decks the global bending moments. The loading on the hull-girder is caused by time-varying still water (e.g. its own weight) and wave loads in-plane of the plates and out-of-plane loads are composed of static and dynamics pressures. In passenger ships, the special feature is a large number of openings in the bulkheads and decks. When optimized for weight, this results in thick bulkheads and thin decks. The lightship weight can be up to 80% of the total weight of the ship, **so weight reduction in hull structures means significant improvement** of the ship performance. In ice-going vessels, the main difference is a smaller number of openings and the fact that the side plating has to tolerate **high local loads from ice impacts under low temperatures**. The ships will be docked every 3–5 years for inspection and repair. In both cases, the bottleneck of design is fatigue strength. This involves load assessment, the response analysis of the structure, and strength level definition. Thus, the HIGHMARINE project focused on holistic assessment of fatigue in high-strength steels. The investigated materials were nominal yield strengths of 355MPa, 460MPa, and 690MPa. Offshore, the main differences among ships are the lifetime of +50 years, typically very thick sections, n**o chance to dry-dock the structures**, a harsh environment in a fixed location (i.e. cannot be changed by route selection), and cold temperatures. Due to this, the damage tolerance of materials becomes crucial and the designers need to make sure that the structures can be operated safely even with existing cracks. Therefore, this issue was the focus in the EXTREMEST project.

Results Basis for design standards

The fatigue research was initiated with the creation documentation of the application case needs. In the previous FIMECC LIGHT program, it was proven that the **base materials, namely steel plates made and processed in Finland, have superior fatigue strength** in comparison to the design curves from the classification society (Remes et al., 2013). These design curves consider quality levels on a world scale. **In order to exploit this competitive advantage, a negotiation with the authorities was needed**. The discussion with the classification society led to the **implementation of a prototype structure of a cruise ship** in operation, with the aim of gaining operational experience. This means here the collection of detailed response information in the highly loaded locations, but also global operational data on prevailing wave conditions. In addition, it was recognized that the test series made earlier in FIMECC LIGHT needed to be extended to make statistics more reliable. It was also recommended that the structures under variable amplitude, or random loading are investigated. In DIMECC BSA, these experiments were carried out. The steel was from SSAB and the production of the test specimens was according to the Meyer Turku Shipyard production process. This process included plasma cutting, grinding, and the sandblasting needed for painting. The results confirmed the findings from Remes et al. (2013): fatigue strength is indeed far better than the current rules allow. The reason for this is still under investigation, but the influence of surface integrity, namely superior surface roughness and compressive residual stress, are the key factors. As the rules limit the maximum stress in the design with the so-called f1-factor, a more holistic analysis of design philosophy is needed, since it seems that the bottleneck of design has been shifted from fatigue strength to another limit state (see Figure 2).

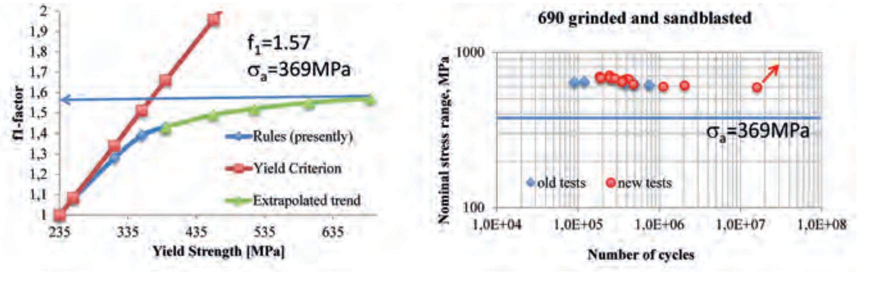

Figure 2. **Left: Extrapolation of material factor f from the present rules, and the allowed σ_a stress level in comparison to observed fatigue test results with real production output**

Lightweight solutions made from steel in marine applications are always welded. It is well known that the welding can remove the benefits gained by increased yield strength, as it causes initial flaws such as weld undercuts and distortions. This is the reason why classification societies adopt a single SN curve for all steels with any yield strength. This approach is conservative. **The conservatism is harmful for shipyards that have high production quality**. Therefore, an experimental campaign was initiated to clarify the issue through scientific data (Peltonen, 2014; Lehtimäki, 2014; Remes et al., 2015; Lillemäe et al., 2015; Liinalampi et al., 2016, Lehto et al., 2016, Remes et al., 2016). A plate thickness of 4 mm was considered with a nominal yield strength of 900MPa. Plasma arc (PAW), submerged arc (SAW), and metal active gas (MAG) welded specimens were tested under constant amplitude loading with a load ratio of R=0.1. The results were analyzed for nominal, structural, and notch stress methods that are commonly used in design; see some examples in Figure 3. **The setting was realistic for future materials and design methods to be used in ship structural design.**

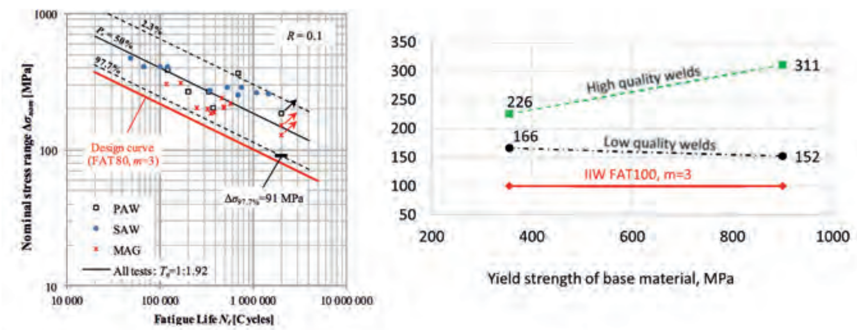

Figure 3. Left: Fatigue strength of welded 4-mm thick plates with yield strength 900MPa in a nominal stress framework. Right: Improvement of fatigue strength at two million cycles (based on the structural stress method) as a function of material yield strength

The main result was that when the production process is optimized and variation in weld geometrical properties is modest, **fatigue strength improves significantly**. Further improvements can be obtained with weld post-processing techniques. Yildirim (2015) and Yildirim et al. (2016a, 2016b) have presented several techniques for such improvements based on HFMI and TIG dressing. Fatigue strength improvements are also obtained for variable amplitude loading, which causes relaxation of beneficial compressive residual stress (Mikkola et al. 2016, 2017a, 2017b). Mikkola et al. have also **proposed design guidelines** for the International Institute of Welding. This is an essential step in getting the technique into industrial use, the as IIW often defines the basis for the rules. During

There is significant unutilized potential in applications of high-strength steel in marine and offshore applications.

the writing of this report, fatigue tests have been continued with the specimen from the shipyard welding process and with plate thicknesses of 15mm. There seems to be significant potential in applications of high-strength steel in cruise ships, ferries, and Arctic vessels.

In offshore-related investigations, the key question has been the use of high-strength steels in these structures, which are exposed to extreme environmental conditions caused by wind, waves, and ice, but also by temperature differences and the loading and offloading procedures of, for example, FPSOs (Floating Production, Storage and Offloading Units). As these structures are often location specific and dry-docking is an economically unacceptable option, crack arrest toughness becomes a crucial research question. The research has been focused on ultra-high-strength steels (UHSS) in this project (yield point at 960MPa; Wallin et al., 2016) and a consideration of sub-sized specimens (Wallin et al., 2016a; which are important when thin offshore structures are of interest) and a master curve approach (Wallin et al., 2015a, 2016b). The data based on the proportional transition temperature (TFa0.4kN/mm*B) indicates that the crack arrest temperature requires a similar shift to the normal transition temperature. However, the conclusion is based on limited data and the derived relation might change slightly when more data is included in the statistical analysis. As the established relation does not show significant dependency on the material's yield strength, the developed relation seems well suited for all types of steel, including UHSSs. These investigations were also extended to very high-strength steels (VHSS) in Wallin et al. (2015b). All this means that the modified (accounting strength) T0-TCV28J-transition temperature correlation is applicable to both low- and high-strength steels, enabling full utilization of the results in design for better products.

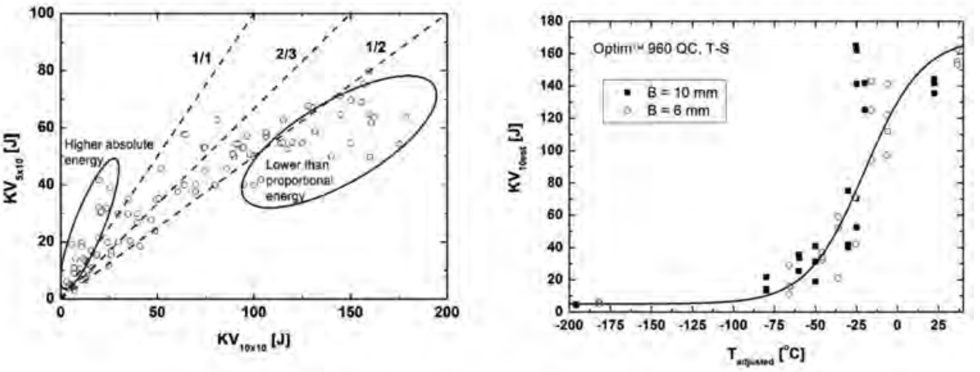

Figure 4. Left: Example of impact energy relations between sub-sized (5x10 mm) and full-sized (10x10) CVN specimens; Right: Example of energy conversion for individual specimens for ultra-high-strength steels (Wallin et al., 2016b)

Conclusions

Utilization of high quality leads to competitiveness

The research shows that we have the right materials and production processes in Finland. We also have a co-operative, academic/research, and industrial community that can utilize these materials by understanding the physical processes associated with strength properties, but also with application cases. This combination can be used to push the boundaries of the present rules and guidelines. In essence, the process can involve different levels of impact, ranging from prototype acceptance, to company-level acceptance or implementation, to design rules that can be used globally. The cases mentioned above can be categorized in each one of these stages of maturity. The right balance must be found for the Finnish maritime community to keep a competitive edge over others in the selected fields, such as cruise and ferry, Arctic, and offshore steel structures. However, a lot remains to be done.

Outlook

The process continues

We need to continue these development processes as our competitors do the same globally. Meanwhile, our national funding instruments are undergoing significant changes. The Finnish maritime cluster is used to fluctuations in markets, and therefore it will adapt itself to these significant changes. The main direction of applied research is to test the concepts in large prototype structures. Therefore, it is recommended that mock-ups be built and tested to gain understanding of the scalability of the found solutions. We need to create a design basis that accounts for better quality. The limit states that must be considered are fatigue, ultimate ductility, fracture tolerance, and stability in compressive loads; an accidental limit stage is not yet considered widely in the marine structures community in rules, but scientific and R&D activities are considerable due to the Costa Concordia accident and increased activities in northern sea routes and the Arctic. The fatigue strength of steels up to 690MPa shows the potential in cut surfaces without welds. The experimental data has been extended and could be used in company-based approval of the concept. However, this involves a process that has been left out of the present project. One issue to be faced in this process is to investigate the relaxation of residual stresses in the processed surface layers of the specimens. As these are production-induced, they are real. However, when ships sail, they experience variable amplitude loads that can relax these stresses. Therefore, the results obtained and shown in Figure 2 should be updated to include this effect. At the time of writing this report, it is difficult to conclude future work holistically from the welded structures, but it is clear that the welding processes must be optimized to balance between strength (e.g. fatigue, ductility, fracture tolerance) and productivity (e.g. flatness and residual stresses, welding speed). HFMI has shown its potential as a way to improve welded joints, but it must be tested in a large-scale industrial setting such as shipyards.

Company impact

"The greatest benefit of the use of high-strength steel in ship structures will be weight reduction and more efficient production."

***Ari Niemelä,** manager, Hull Basic Design, Meyer-Turku*

"In this project, we have got very remarkable results toward a more sustainable and lighter world."

***Pertti Mikkonen,** product development manager, SSAB*

Further information

KEY PUBLICATIONS:

Lillemäe, I.; Liinalampi. S.; Lehtimäki, E.; Remes, H.; Romanoff, J.; Lehto, P. "Fatigue strength of high-strength steel plates on very high-cycle fatigue regime", Marine Structures, 2017, *(to be submitted)*.

Mikkola, E; Remes, H; "Allowable stresses in high-frequency mechanical impact (HFMI)-treated joints subjected to variable amplitude loading", Welding in the World, Vol 61, 2017, pp. 125–138.

Remes, H.; Jelovica, J.; Romanoff, J.; Lehto, P.; Liinalampi, S. "Fatigue strength modelling of high-performance welds using local approaches", PRADS 2016, International Symposium on Practical Design of Ships and Other Floating Structures, 4th – 8th September, 2016, Copenhagen, Denmark.

Wallin, K., Karjalainen-Roikonen, P. and Suikkanen, P., "Sub-sized CVN specimen conversion methodology", 21st European Conference on Fracture, ECF21, 20–24 June 2016, Catania, Italy. Ref. b

Wallin, K., Pallaspuro, S., Valkonen, I., Karjalainen-Roikonen, P. and Suikkanen, P., "Fracture properties of high performance steels and their welds", Engineering Fracture Mechanics, Vol. 135, pp. 2015, pp. 219–231.

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DESIGN BEYOND CURRENT CODES

P2
SP2

Timo Björk/Lappeenranta University of Technology
Pertti Mikkonen/SSAB

New design rules for welded structures made of ultra-high-strength steels

Background

Today's steel structures set high demands on the load capacity of welded joints, and this will even increase in the future. This requirement is generic, but it is especially important for fatigue loading. On the other hand, new high-strength steels offer a possibility to reach these requirements, but utilizing this potential requires changes in current design codes. Design engineers must be capable of designing and analyzing more complicated welded structures made of these new types of steels, for safe, energy-efficient, and exceedingly demanding applications. Consequently, the demand for new design guidelines and calculation methods is obvious, and these guidelines will be the basis of new design codes in the future. Additionally, the research forms the basis for changing the rules used in different classification societies, such as DNV, GL, and BV.

In addition, the quality of welding has increased recently, or at least it is better known how the parameters should adjust in order to reach a better fatigue life in welded joints. The improvement can be reached either by choosing proper welding processes and their parameters, or by post-treatment of the weld, or using both approaches. The improved quality must be described as a new design curve. The increased strength of structural steel combined with improved weld quality can be utilized to enhance the performance of welded structures. This advantage should be considered in design and in practice during the manufacturing phase. The utilization of this potential requires new research and guidelines for entire production chain, which includes design, fabrication and inspection.

In addition to fatigue strength, the ultimate capacity of the joint is important. Consequently, the load-carrying and deformation capacities must be estimated, and new design methods based on analytical or numerical methods are needed.

Objective The primary goal of the research theme is to produce an improved **fatigue design method** for high-quality welded joints and cut edges made of high- or ultra-high-strength steels. The second goal is to find the **fatigue properties of stainless steel welded joints** in the as-welded (AW) or post-treated condition. The third goal is to create **analytical and numerical methods to define the ultimate capacity of welded joints** made of ultra-high-strength or armor steels.

Results The research was carried out at Lappeenranta University of Technology (LUT) in close collaboration with industrial partners. All the academic results are presented here independently in their own framework. The industrial highlights are described at the end of this chapter.

Fatigue

3R method

The fatigue design method presented in design codes and recommendations, such as nominal, hot spot, effective notch stress methods, and fracture mechanics approaches, seems not to be suitable in considering the benefits and risks involved in fatigue assessment of welded joints made of UHSS. The reason for this is that the current versions of those methods do not take all the important parameters and quality into account. Consequently, a novel, more comprehensive method was developed to consider essential fatigue parameters such as material strength (in terms of ultimate tensile strength), residual stress, applied stress ratio, and local weld toe geometry. All these parameters alone, and especially together, will increase the accuracy of the calculation method, as a consequence, the designer can estimate, for example, the effect of HFMI for a certain steel grade, and also considering the effect of the applied stress ratio.

However, the method can still be rather simply applied in practice, because the additional parameters are quite easy to define or measure. If they are not known, default values on the safe side are used. As a result, a new, general, master curve method, called the 3R method, was created.

$$\Delta\sigma_k^m N = \left(1 - R_{local}\right)^{\frac{m}{2}} C_{ref}$$

Of course, the method was verified by experimental tests, as illustrated in Figure 1.

A novel 3R method developed and proven as a promising tool for fatigue design of welded and cut edges.

The method provides more accurate fatigue strength assessment compared to conventional methods. It is the most versatile available method, especially for UHSS, where weld quality, the effect of residual stresses, and stress ratio are essential parameters. This method can be used in addition to fatigue life estimation for certain cases, and also for:

- choosing the optimal steel grade
- considering the post-treatment (HFMI)
- setting the requirements for weld toe geometry
- analyzing the effect of its own weight

Generally, the 3R method enables efficient and safe fatigue design for UHSS welded joints and structures.

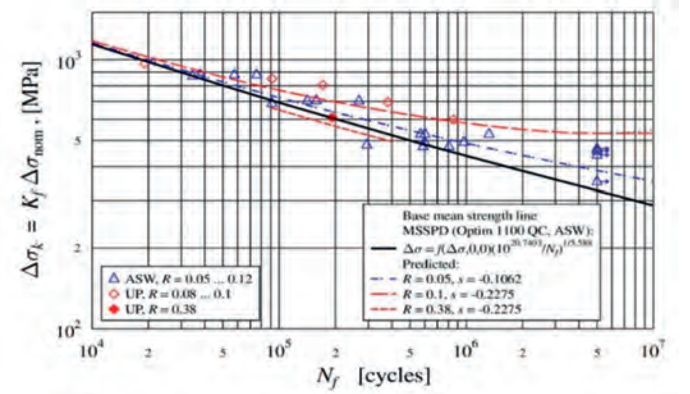

Figure 1. **Proving the validation of the 3R method by experimental results**

The 3R method was developed further for the assessment of the fatigue strength of cut edges in steel plates. The main parameters were steel grade, cutting process, surface quality, and applied stress ratio. The results obtained by conventional fatigue assessment methods did not match the experimental fatigue test results, but the modified application of the 3R method agreed very well with experimental tests, as illustrated in Figure 2.

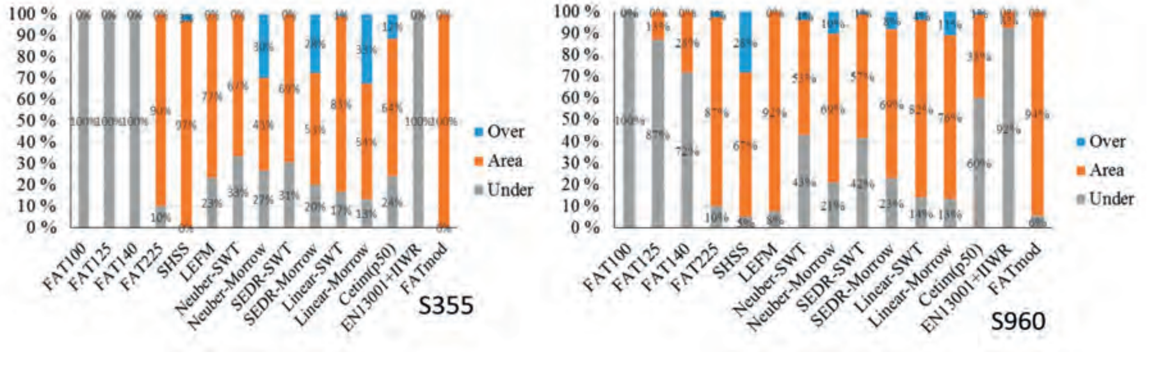

Figure 2. **Average percentage distribution of fatigue strength for tested steel grades; the last column is the new 3R method (=FAT-mod) and obtains the best fit, whereas the other theoretical methods under- or overestimate the proven experimental capacities**

Consequently, the novel, project-developed 3R method seems to be a very promising tool for fatigue design of welded joints and cut edges.

Fatigue properties of UHSS

A conventional finite element model equipped with nonlinear kinematic isotropic hardening parameters tuned through experimental low-cycle fatigue (LCF) data was used to simulate the cyclic transient response of the material in question. The cyclic softening and following stabilization were caught precisely, with only a slight discrepancy in the overall shape of the stabilized hysteresis loops (which are indicative of absorbed plastic strain energy) at different strain amplitudes. The simulated hysteresis loops were used to obtain the cyclic stress-strain curve, which showed a high degree of agreement with the experimental curve (see Figure 3).

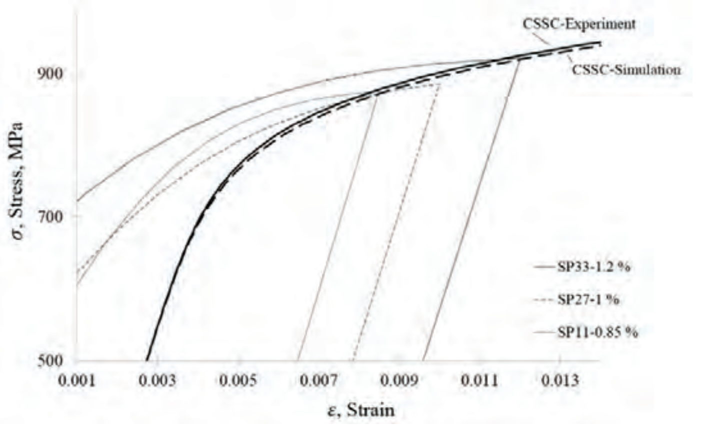

Figure 3. Hysteresis loops at different strain amplitudes, and cyclic stress-strain curves from simulation and experiments

The study proceeded to analyze the LCF behavior of notched specimens. A non-linear finite element model using the CSSC as a material response yielded the most accurate life estimations compared to analytical approaches, such as the linear rule, Neuber's rule, and the strain energy density method, the last two of which were also used in modified form for the plane strain condition. In order to obtain a comprehensive comparison, the most advanced method based on critical distance philosophy, namely TCD, was also utilized. This method of post-processing the results of the same non-linear finite element model significantly reduced the conservatism seen in life estimations by other methods, including the finite element method itself, especially in specimens with high stress concentration factors (see Figure 4a). This study is currently ongoing to evaluate the precision of the TCD method when the notch critical area is defined by the crystal plasticity concept.

A model based on the artificial neural network (ANN) concept was developed to estimate the stress concentration factor (SCF) of fully penetrated T-welded joints in as-welded and TIG-dressed conditions. This mathematical model could be trained in order to perform the SCF calculations. More than 320 finite element models were used in order to train, validate, and test the model. A comparison of the model to available empirical equations for SCF calculation showed that this model not only yields the closest estimations to FE (see Figure 4b), but was also able to make acceptable SCF estimations for the configuration in which the local weld parameters were out of range of those used for training the network. The empirical equations, however, showed no ability to make estimations out of their valid ranges. The study is currently ongoing to extend the approach to butt welds, including axial misalignment effects.

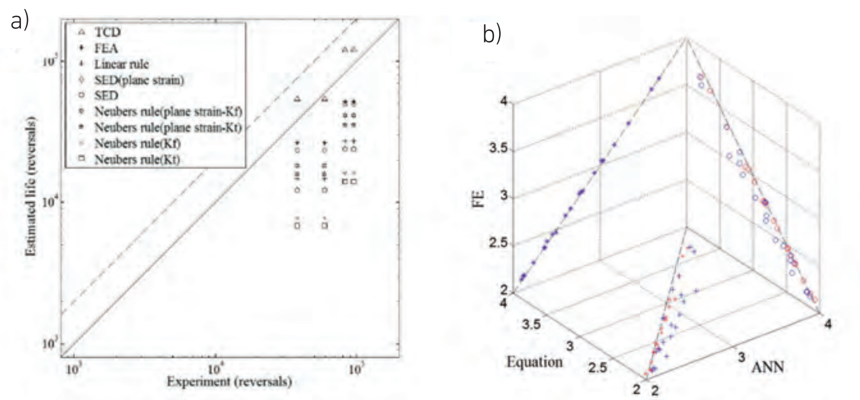

Figure 4. a) Comparison of estimated and experimental lives for notched specimens with R = 1.5 mm; and b) comparison of the calculated SCFs using the empirical equations, ANN-based model, and FE for axial load

Effect of local constraint and loading

The fatigue assessment of a welded joint can be carried out based on nominal, structural (hot spot), local notch stress (ENS), or linear-elastic fracture mechanics (LEFM) approaches, as illustrated in Figure 5.

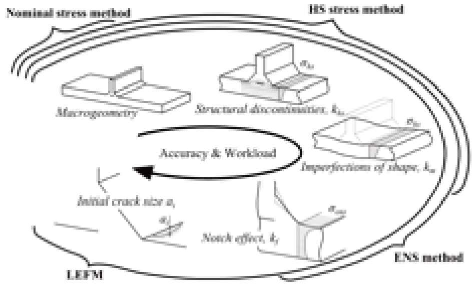

Figure 5. Consideration of local effects in widely used fatigue analyzing methods

When the nominal stress approach is used, both the degree of bending (DoB) and joint symmetry are ignored. In the hot spot approach, the DoB is ignored and the joint symmetry is considered in some cases, using FAThs = 90 MPa instead of 100. When the ENS or LEFM approaches are used, the symmetry of the joint and the DoB can be considered in more detail. In this investigation, it was found that both of those effects can have a significant impact on the fatigue strength of the joint and should be considered in practice. This investigation proves that axial loading creates higher local stress concentration in a symmetric joint than in an asymmetric joint, but the bending moment has the opposite effect. Both the applied ENS and LEFM methods proved similar behavior. In addition, the test results agreed with theoretical results, except in the case of bending loading, where the asymmetric joints were shown to have better fatigue strength than symmetric joints.

Low-cycle fatigue of UHSS

Low-cycle fatigue (LCF) is important to consider in many applications made of UHSS. A typical example is mobile lifting systems, such as a passenger hoist, where lightness is a desired feature. In this task, the LCF of UHSS grade S960 was investigated using test specimens with laser processes or water cut edges, butt welds made by GMAW and laser, and load- and non-load-carrying X-joints. Some test specimens were HFMI treated. The axial tensile load was applied. The experimental results are seen in Figure 6.

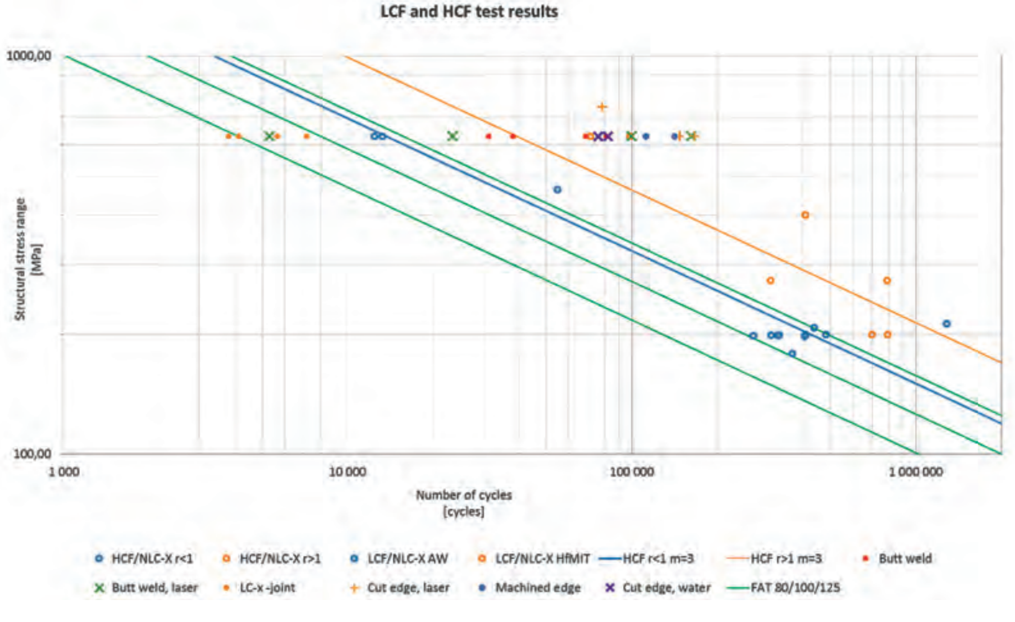

Figure 6. Low-cycle fatigue test results of S960

The test results were in accordance with results from a high-cycle regime. The experimental results also matched well with theoretical results calculated by ENS, where the real weld toe geometry was considered. It was unexpected how better weld quality also brought about better fatigue strength in the LC regime, and how the same effect was seen in the HFMI treatment.

Fretting fatigue

The main goal of this study was to develop a mathematical model for fretting fatigue, and a life calculation tool for bolted joints, as seen in Figure 7. The primary material has been ultra-high-strength steel, because these steel grades are more difficult to weld and therefore other joining techniques would be beneficial. Due to the nature of the fretting phenomenon, the study comprises a numerical as well as an experimental part.

The results so far have shown the following aspects:

- Even though the joint is basically a complete contact, the fretting-critical area in a bolted lap joint is not at the edge of the plates but near the bolt holes.
- In untreated surface conditions, ultra-high-strength steel (S960) is more prone to fretting than regular S355 grade structural steel, but machining of surfaces seems to fix this problem (although more test results are needed for validation).
- The crack initiation phase dominates fatigue life.
- For the fretting fatigue life calculation, a SWT parameter-based approach produces satisfactory results but is sensitive to used parameters.

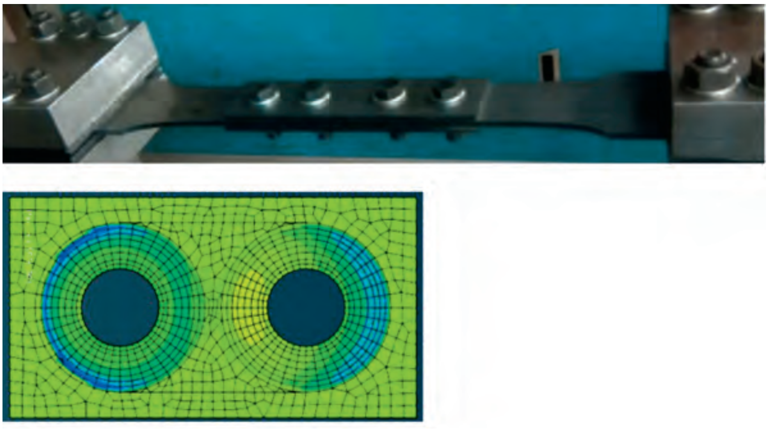

Figure 7. Test specimen attached to the test machine, and the relative slip between the base and face plate, where the deep blue arc reveals the most fretting-critical area

Fatigue of stainless steels

The fatigue strength of the base material and welded joints made of duplex and super-duplex stainless steels was investigated. The specimens consisted of base material cut by different processes and of welded joints with butt or fillet welds and with or without HFMI treatments. The summary of the results is seen in Figures 8 and 9.

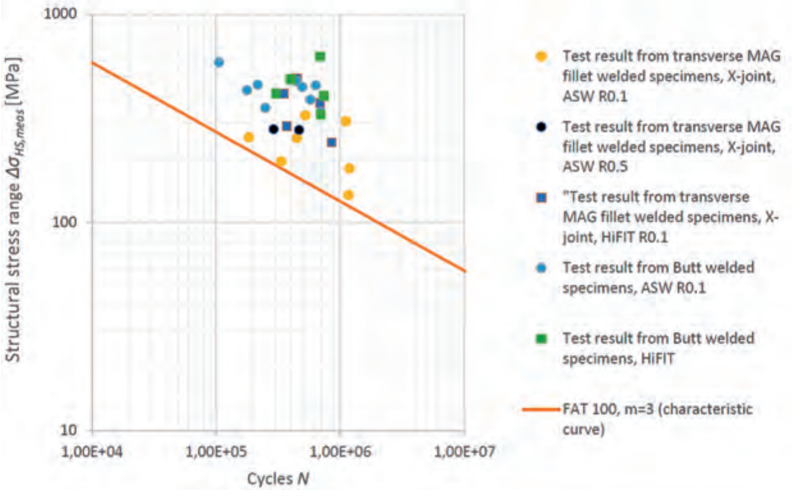

Figure 8. Fatigue strength of duplex stainless steels

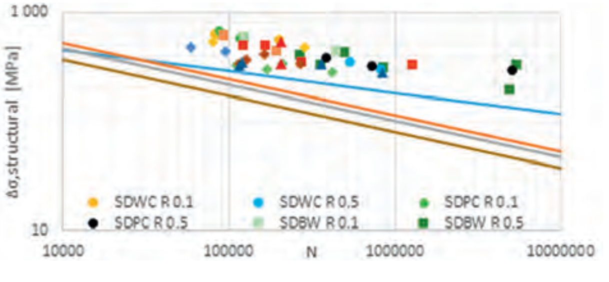

Figure 9. Fatigue strength of super-duplex stainless steels

Improving methods

In this project, the high-frequency mechanical impact (HFMI) treatment was investigated as a fatigue improving method for S960, and in other simultaneous projects, other methods, such as TIG and laser dressing and MAG brazing, were investigated. Generally, HFMI obtains very good results and is the best method if the benefit due to high compressive residual stresses can be exploited in service. TIG dressing creates the best weld toe geometry and consequently can be competitive for some applications with HFMI. MAG brazing is also a promising method, but joint preparation must be carried out carefully and proper process parameters must be known. Again, the 3R method is a good method to explain the experimental results and find the best solutions for certain applications, as illustrated in Figure 10.

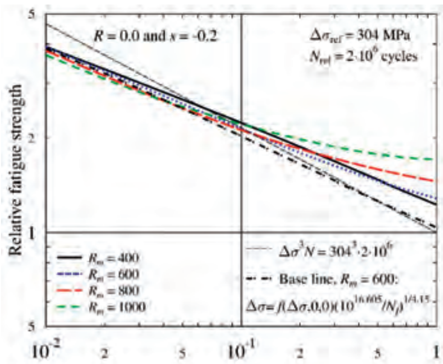

Figure 10. The 3R method can be used to predict the effects of post-treatments on welded joints; in this example, the HFMI treatment created compressive residual stresses, which are 20% of the ultimate strength

Static strength

Novel critical plane approach

There are several approaches to define the critical load-carrying capacity and the critical failure plane in an axially loaded plate. The criteria can be based on several hypotheses, such as principal stress (α = 0), Tresca (α= 45 deg.), and octahedral planes (α = 35.3 or 54.7 deg.). However, all these hypotheses obtain the same loading capacity $F= Af$, where A is the cross-section area bt (= plate width times thickness), and f is the axial strength (yield or ultimate) of the material.

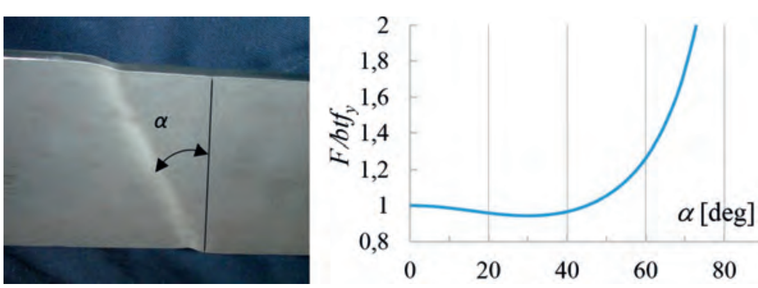

Figure 11. The critical plane in an axially loaded plate

However, the experimental investigation pointed out that failure does not occur at any of those theoretical angles, but at an angle of 30 degrees, as seen in Figure 11. Consequently, the capacity must be less than predicted by conventional methods, which means $F \leq Af_y$ otherwise it would not happen in practice. Therefore, a new critical plane approach was developed, which obtained the critical angle

$$\alpha = \arccos\frac{\sqrt{3}}{2} = \frac{\pi}{6}\,\text{rad} = 30\,\text{deg}$$

and the capacity

$$F = \frac{btf_y}{\cos\alpha\sqrt{3-2\cos^2\alpha}} = \frac{2\sqrt{2}btf_y}{3} = 0.943btf_y$$

Although the numerical difference is small, it has an important practical application. In some older design recommendations, inclined welds were recommend in order to improve the loading capacity of axially loaded structures and thus avoid the weakening effect due to softening. This approach proves that the proposal is wrong, which was also proved experimentally. Figure 12 illustrates how the inclined angle must be at least about 60 degrees in order to obtain any additional capacity. This means double the weld length and thus, it is not recommended.

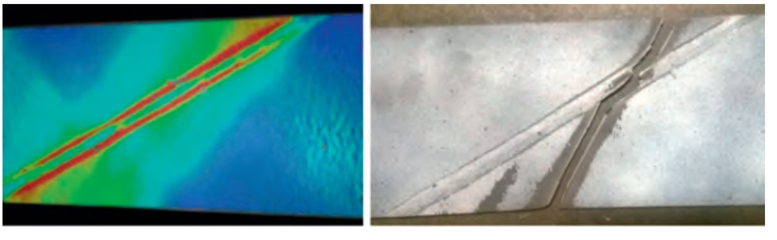

Figure 12. **When the angle of the weakened HAZ exceed an angle of 60 degrees, the failure takes place in a critical plane at an angle of 30 degrees**

Fabrication effect on ultimate capacity

The direct-quenched UHSS material seems to be sensitive to welding or other types of heat input. Although it is not possible to avoid a softened HAZ, smaller sizes of HAZ lead to a stronger constraint. The HAZ constraint creates a hydrostatic stress component and thus increases the yield stress of the HAZ and the ductility of the joint. Depending on the welding procedure, the HAZ can create a shape similar either to a plane strain or to a plane stress component. The analytical approach predicted an increase of 65% and 12.5% in the magnitude of the stress in the loading direction for the plain strain and in plane stress in the HAZ, respectively. The experimental and the numerical analyses gave similar results, as illustrated in Figure 13.

High-speed laser welding with high power creates a narrow HAZ in the form of a plane strain component, which results best joint capacity. Based on the experimental, analytical, and numerical findings, UHSS weldments should be welded with a very steep groove angle to attain the maximum constraint HAZ in a plane strain shape.

Post-welding treatments such as TIG dressing and HFMI have no significant effect on the strength and ductility of the joint after butt-welding of UHSS using GMAW. The large HAZ caused by GMAW remains the factor determining the joint's strength and ductility.

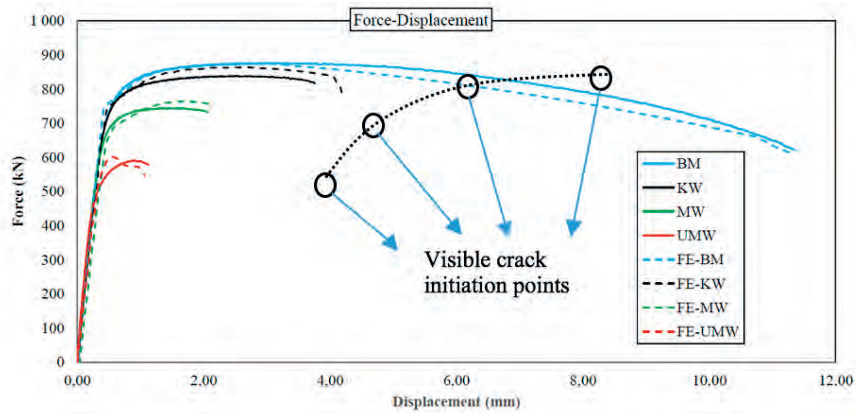

Figure 13. **Force-displacement curves from experimental and numerical simulations (the considered gauge length is 80 mm from the middle of the specimen). (BM: base material, KW: keyhole welding, MW: match welding, UMW: undermatched welding, FE: finite element)**

Capacity of RHS joints

The conventional way to define the capacity of a weld in a tubular joint is to assume evenly distributed stress along the joint perimeter. However, this method does not work if the joint is made of UHSS. A more sophisticated approach is needed, in which the membrane stress has a different role compared to secondary bending and the local notch stress component. In addition to stress distribution, the adjacent HAZs with distinguishing properties must be considered. The weakest link of the joint and its properties must be defined. A new design method for welded joints based on this approach will be presented. In Figure14, the essential joint effects are illustrated.

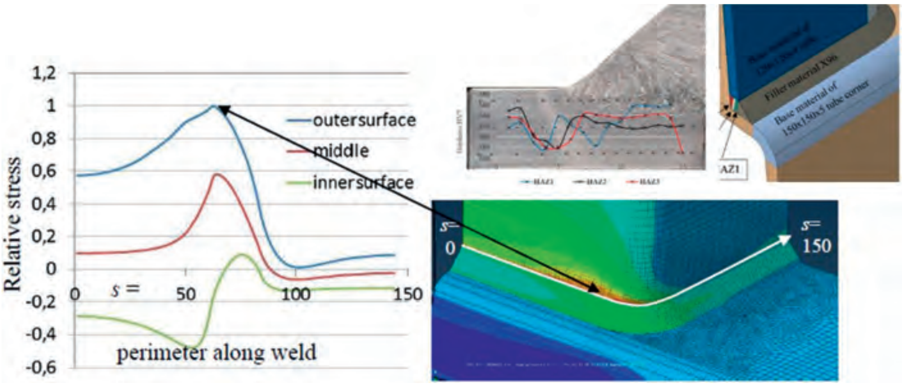

Figure 14. **Stress concentrations and hardness distribution in critical regions of tubular joint**

Constraint effect

The study based on finite element analysis showed that the local constraint caused by the joint has a significant effect on both ultimate displacement and loading capacities. The constraint effect has a beneficial effect on the joint static ultimate capacity, and the strength of the constraint is dependent on the joint geometry. On the other hand, the width and depth of the heat-affected zone also affect the joint ultimate capacity, and when the width of the heat-affected zone exceeds a specific threshold value, the benefits of local constraint will vanish, and the fracture occurs at the HAZ. Figure 15 shows the effect of HAZ width on the dominating failure mode. If the HAZ is narrow, the constraint forces the fracture to occur in the base material as an inclined fracture, but when the HAZ is very wide, the fracture occurs at the HAZ.

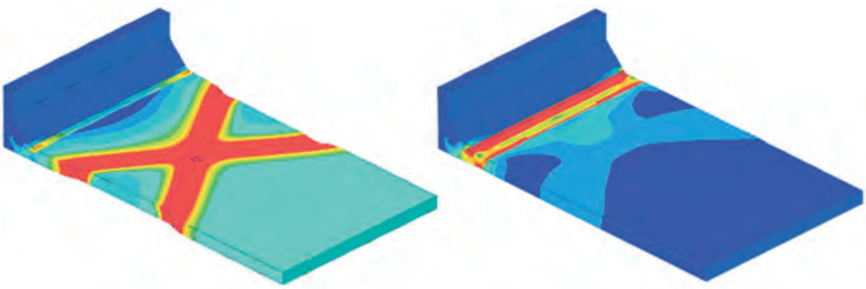

Figure 15. **Fracture modes for narrow (left) and wide (right) heat-affected zones in non-load-carrying X-joint (maximum principal strain)**

Material modeling of armor steel

The industry-driven study concerning SSAB´s novel direct-quenched armor steel was divided into two parts. In the first part, the main focus was on the effective utilization of the steels in the protective structure of an armored vehicle, and in the second part, to identify the parameters and characterize the material properties needed for the capacity simulation model of the chassis.

The main challenge in the development of armor for a mobile application is to minimize the weight of the structure while ensuring a certain level of protection for the occupants. The main result of this part of the study was the development of a lightweight armor with excellent protection properties for the Protolab PMPV 6X6 armored vehicle (see Figure 16).

Lightweight armored structure with excellent ballistic protection demonstrated in the Protolab PMPV 6X6 armored vehicle.

Figure 16. **PMPV 6X6**

During the design process, it was noticed that an effective way to avoid a fracture and to minimize the impact on occupants is to utilize local yielding in order to increase the energy absorption and the displacement capacity of the structure. Utilization of local yielding in the structure, which must be able to withstand loads generated by mine explosions, is not a trivial task. In order to achieve this, numerical simulations capable of failure assessment must be used during the design process. Accurate material models have a key role in the development of reliable simulation models. Thus, the second part of the study focused on the failure and damage modeling of direct-quenched armor steels. According to the study, a tabulated Johnson-Cook and GISSMO model might also be suitable for these steels. The methods used in order to calibrate these models for the base material are described in the literature, but there is no information about the use of these models for welded structures. Thus, the research work will continue.

Industrial deliverables

Table 1 presents a summary of the research outcomes of the industrial participants involved in this sub-project.

Table 1. **Research outcomes of participating companies**

COMPANY	RESULTS	REFERENCE TEXT
SSAB	Design and fabrication parameters for UHSS Application of UHSS structural steels, armored steel and wear-resistant steels	All except stainless steel
Kone-cranes	Novel method for fatigue assessment of cut edges New concept for optimizing the crane components by exploiting UHSS Innovative way to make beam components for cranes	3R method
Outotec	Fatigue design of duplex steel Fatigue design of super-duplex steel Improving the fatigue strength of duplex steels by HFMI treatment	Stainless steels
Protolab	Design and fabrication of new armored personnel carrier Research work involved in design and fabrication of welded joints made of armored steel	Armor steel
Delta-marin	More efficient fatigue analysis methods for ship structures and details	
Arctech	Welding parameters for high-strength steels used in Arctic ship	

Impact

The results of this sub-project are remarkable in two ways: the theoretical understanding of the behavior of welded joints made of UHSS is now at much higher level than at the beginning of the project, and on the other hand, the results can be applied in practice and can bring technical and consequently also economic benefits in their application. The impact of the 3R method, in particular, cannot be highlighted too much. Based on these results, Finland is now a leading country in the design of welded

Theoretical understanding of welded ultra-high-strength steels brought to serve practical design.

joints made of UHSS. It is important to continue the research work so that these results are widely and easily utilized in the excellent properties and competence of Finnish export products.

Company impact

"The use of high-strength steels is more challenging, and compared to conventional steels, it requires better skills from designers and manufacturers. This project has given a lot of understanding of the fatigue and design criteria for light, sustainable structures made of high-strength steels. The information is also needed in developing novel high-strength steels, and for SSAB it is very important to be able to give this information to customers."

***Pertti Mikkonen,** product development manager, SSAB*

"The project enabled the straightforward cooperation between companies and research institutes. During the project, good and in-depth co-operation was born with subcontractors.

During the project, knowledge was increased and problems solved, for example in the field related to thermally cut edge and fatigue time estimation. The concrete calculation method was documented in the form of a dissertation. The results obtained will have a positive impact on the competitiveness of the welded plate structures.

The project provides the first experience in the utilization of high-strength steel, and it offers opportunities, challenges, and constraints in order to improve product competitiveness in global markets."

***Juha Peippo,** senior chief engineer, Konecranes*

" – Competitive improvement in product cost due to the increased FAT classes for welded duplex steel

– Competitive improvement in product cost due to the increased FAT classes for HIFIT-treated welded duplex steel

– Improvement in product manufacturing quality by testing workshop-manufactured test plates."

***Ville Strömmer,** product manager, OKTOP Atm Equipment, Outotec*

Further information

KEY PUBLICATIONS:

Björk T., Penttilä T., Nykänen T. Rotation capacity of fillet weld joints made of high-strength steel. Welding in the World, 2014. Vol. 58, Issue 6.

Björk T,. Nykänen T., Valkonen I. On the critical plane of axially loaded plate structures made of ultra-high-strength steel. Welding in the World, 2016.

Nykänen T., Björk T., Mettänen H., Ilyin A.V., Koskimäki M. Residual strength at −40°C of a pre-cracked cold-formed rectangular hollow section made of ultra-high-strength steel – An engineering approach. Fatigue and Fracture of Engineering Materials and Structures, 2014. Vol. 37, Issue 3. pp. 325–334.

Nykänen T., Björk T. A new proposal for assessment of the fatigue strength of steel butt-welded joints improved by peening (HFMI) under constant amplitude tensile loading. Fatigue & Fracture of Engineering Materials & Structures, 2016. Vol. 39: 5. pp. 566–582. doi: 10.1111/ffe.12377.

Nykänen T., Björk T. Assessment of fatigue strength of steel butt-welded joints in as-welded condition – Alternative approaches for curve fitting and mean stress effect analysis. Marine Structures, 2015. Vol. 44. pp. 288–310. doi: 10.1016/j.marstruc.2015.09.005.

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Arto Lehtovaara/Tampere University of Technology
Gabor Szanti/ATA Gears Ltd

Gears with extra high torque density

Summary of the project's motivation and achievements

MOTIVATION: Mechanical power transmission components, such as gears and bearings, are widely used basic elements in mechanical engineering. The most challenging applications for these components can be found in large-scale wind turbines and ship propulsion systems representing the wind power and marine industries. This kind of large-scale heavy rotating machinery needs improvements in energy efficiency, which requires components and structures with minimized mass and dimensions. The target of high-power transmission capacity, especially high torque density, sets new requirements in the case of hardened steels, as well as for the design of the components. Gear and gear-drive manufacturing is an important export industry in Finland. In addition, high-quality power transmission drives and the related design knowledge are of outmost importance, as these components are often inseparable parts of Finnish worldwide export products. Material technology plays a key role for improving the competitiveness of wind energy and maritime, and development in these areas is seen as very important.

THE AIM of the project was to improve the load-carrying capacity of case-hardened steel gears, and especially the fatigue life of the tooth root and flank surface in terms of material and surface properties. An important goal was to produce the knowledge and preliminary evidence needed by international classification societies to allow gear loading beyond the present design codes. The scientific goal was to evaluate the fatigue life of gears by developing advanced test methods, carrying out experimental fatigue tests, and characterizing the appearing surface damage and material properties, as well as to produce design guidelines, including for extreme loadings. Another important goal was to develop a numerical gear model to simulate the damage risk based on stresses in the gear contact and tooth root.

The project was divided into three main tasks:

1. Development of a novel type of steel, characterization of material properties and tooth root fatigue tests
2. Experimental evaluation of the fatigue life of gears contacts
3. Modeling and simulation of gears

MAIN ACHIEVEMENTS: In Task 1, the properties of carburizing steels were developed using laboratory-scale melts and testing of their properties after different heat treatments. The achieved results confirm the positive influence of certain micro-alloying elements. The comprehensive evaluation of material properties of reference test gears showed that the used raw material fulfills the tight up-to-date specifications set for FZG gears. The test method was established to carry out tooth root fatigue tests based on the guidelines of the international classification society. The main results were the preliminary S-N curves pointing out a clear improvement in the fatigue limit with the new material compared to the reference material. In addition, it was found that the level of surface roughness, meaning the quality of soft machining, also has an effect on fatigue life.

In Task 2, several test and online monitoring methods were developed and upgraded for the existing TUT FZG gear test rig. The progression of macropitting failure indicated by the number of metallic particles in oil obtained with online particle monitoring correlates well with the damaged gear flank area given by a visual inspection. Successful online particle monitoring helped to minimize the time-consuming visual inspections and provided fundamental knowledge of macropitting behavior. The actual macropitting tests with FZG test gears were based on the guidelines of the international classification society. The measured preliminary S-N curves indicate significant potential for improving gear fatigue life by using gears with a special treatment called isotropic superfinishing compared to the reference gears.

In Task 3, a parameterized gear model was developed for the stress-based analysis in the gear contact and the gear tooth root. A local adaptive FE mesh approach was developed, in which a dense FE mesh zone around the contact point moves along the line of action to speed up the computation. The gear contact pattern along the line of action was computed and analyzed by taking into account multiple tooth contacts, the tooth flank modifications, and shaft misalignments. The model enables optimization of the contact pattern to maximize the load-carrying capacity of the gear pair.

Key results and impacts

Development of a novel type of case hardening steel

The aim of this task was to achieve a novel type of case hardening steel with high fatigue resistance by focusing on non-metallic inclusion cleanliness, grain size, niobium alloying, and heating history during the manufacturing process. This task has synergy with the work on the DIMECC SIMP program covering the steel manufacturer's overall industrial goals.

The properties of carburizing steels were studied by carrying out a literature review as well as laboratory-scale melts and testing of their properties after different heat treatments (Aaltio 2015). The achieved results confirm the positive influence of certain micro-alloying elements. However, the industrial-scale melt was not realized, mainly due to the shortened project time. The comprehensive evaluation of material properties of reference test gears was also realized. It was concluded that test gear raw material fulfills the tight up-to-date specifications set for FZG gears. Some duplicate tests were carried out in Tampere University of Technology/Tampere Wear Center, as well as characterization (SEM+EDS, OM) of the reference material microstructure.

Characterization of material properties and tooth root fatigue tests

The aim of this task was to evaluate experimentally gear tooth root fatigue life using a novel type of case hardening steel, and to characterize the material properties and failure mechanisms. Several parameters affect the fatigue life of components. Although the selected steel has a marked effect on the fatigue life, it is not just material properties that count. The manufacturing process parameters, the surface treatments, the surface roughness, and the geometrical details of the component also have significant roles. The evaluation of tooth root fatigue was done with a servo-hydraulic testing device using a single tooth fatigue test (STF). The main principle of this test is presented in Figure 1. Development of this pulsator type of fatigue testing rig was done according to the suggestions from the international classification society. The origins of fatigue failure were characterized by scanning with an electron microscope and 3D optical profilometer. The microstructural features affecting fatigue behavior were also studied.

Figure 1. The test set-up attached to the servo-hydraulic testing device

Fatigue testing is very time consuming, and the obtained data needs to be statistically evaluated. The fatigue limit needs to be approached from both sides; a certain number of run-outs and failures are needed. The run-out limit was set at 5 million cycles. The material of the reference test gears was 18CrNiMo7-6 and it was delivered by Ovako. Similar tests were run for high-performance case hardening steel. The obtained fatigue test data suggested that with the new material, the limit of tooth root fatigue stress was shifted toward higher values when compared to the reference material performance. The level of surface roughness and the quality of machining of the tooth root area were also found to affect fatigue performance. Intergranular oxidation caused early fatigue failures in some teeth. The fracture surfaces were studied with the scanning electron microscope to reveal the nature of the origin of the fatigue failure. The fracture positions were characterized by the optical profilometer. Figure 2 presents the optical profilometer image of the fracture surface, in which the arrow indicates the direction of propagation of the fracture. The maximum forces were also traced with the strain gauges attached to the tooth root during tests.

A high fatigue stress limit was achieved using novel high performance case-hardening steel.

Figure 2. **The image of the fracture surface of the tooth, as characterized by the optical profilometer. The arrow indicates the direction of propagation of the fracture**

Experimental evaluation of the fatigue life of gear contacts

The aim of this task was the experimental evaluation of the macroscopic pitting fatigue life of gears, using novel types of materials and surface topographies. Macroscopic pitting is one of the most common gear flank failure modes, mainly caused by repetitive Hertzian contact stresses of the mating surfaces. The determination of gear pitting life can be done experimentally by using, for example, an FZG back-to-back test rig, for which a schematic view is shown in Figure 3. The formation of a macropit is typically followed by regular visual inspections and photographing of tooth flanks.

Several test and monitoring methods were developed and upgraded for the existing TUT FZG back-to-back test rig. The main upgraded features were online particle counting from oil, vibration monitoring, shaft torque measurement, and tooth root stress measurement. An offline

Modern methods for testing fatigue life of gears.

method for measuring gear flank profile and topography was developed and implemented, which can be utilized before and after the fatigue tests. Continuous shaft torque measurement was implemented in the test rig pinion shaft, which increased the accuracy and reliability of the test results.

An inductive sensor, detecting solid contaminants (> 70 μm), was implemented in the test gearbox oil outlet for *online monitoring of oil* cleanliness. The progression of macropitting failure indicated by the number of metallic particles in oil obtained with online particle monitoring correlates well with the damaged gear flank area revealed by the visual inspection (Kattelus et. al. 2016). The correlation can be seen in Figure 4.

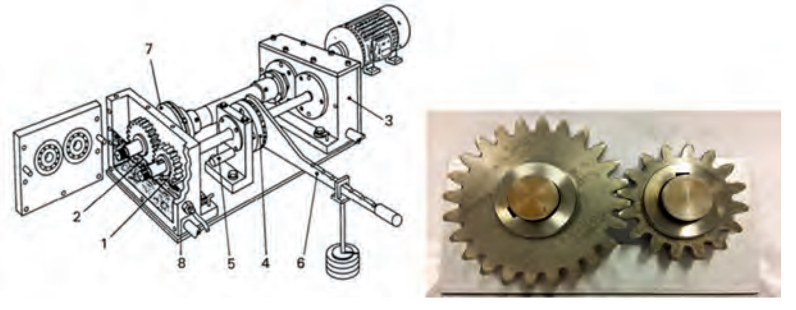

Figure 3. Schematic view of the FZG test rig and the used test gears

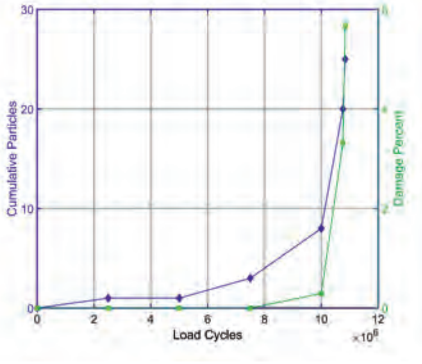

Figure 4. A comparison of the gear flank damaged area and the measured particles in the oil outlet as a function of load cycles

Visual inspection is pretty time consuming and gives information only from one single moment in time. However, time intervals for visual inspections were minimized based on online particle monitoring. In addition, fundamental knowledge of pitting behavior was improved as continuous information related to the progression of pitting was available via online monitoring.

Improved knowledge of pitting behavior via online particle monitoring.

Figure 4 shows that the initiation of damage can be seen earlier with on-line monitoring than with visual inspection.

The primary target of *vibration monitoring* was to find out whether the progression of pitting can be detected using vibration measurements. Vibration acceleration descriptors indicating a peaked signal correlate with the wear of gear contact, but the correlation is not as strong as in wear particle online monitoring. Combining vibration and oil particle monitoring together with monitoring of the main running parameters and photography may offer the most reliable view of the progression of pitting.

The actual macropitting fatigue testing of gears was carried out using modified FZG gears with synthetic gear oil. The preliminary S-N curves of the reference and superfinished test series are presented in Figure 5.

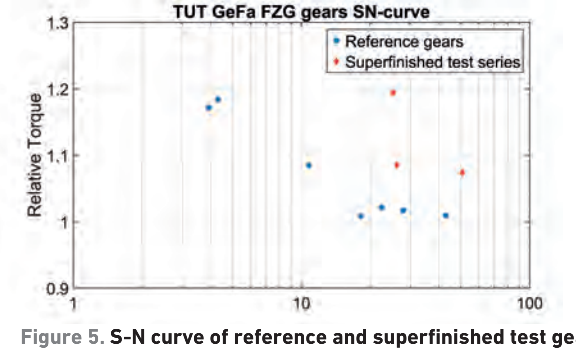

Figure 5. **S-N curve of reference and superfinished test gears**

The material of the reference test gears was steel bar 18CrNiMo7-6 delivered by Ovako. The gears were case hardened to a specific surface hardness of 60 – 62 HRC. After hardening, the gears were ground, resulting in a flank surface roughness of around Ra 0.5 µm. The influence of surface quality on teeth flank fatigue was investigated using a special surface treatment called isotropic superfinishing (ISF). The superfinished test gears were taken from the same material and case hardening patch as the reference gears, but the flank surfaces were further superfinished to a level of Ra < 0,1 µm (mirror-like surface). The superfinished gears were delivered by ATA Gears. A significant improvement in pitting fatigue life (2.5–5 times longer) was observed in the superfinished test series compared to the reference series. The setup of the fatigue test was based on the guidelines of the international classification society. An extremely long testing time with a run-out limit of 50 million load cycles is required in gear flank

Significant improvement of gear fatigue life with isotropic superfinishing of gear surfaces.

tests, with the result that one test may take many weeks even though the test rig is prepared to run overnight with automated emergency stop systems.

The fatigue tests were also carried out in Moventas with a modified FZG-type test rig. Test planning and test methods are prepared in close collaboration with the international classification society. The goal is to improve the torque density of large-size industrial gears, as shown in Figure 6 (Paattakainen 2017). An ATA Gears large-scale full-power (2 MW) bevel test gear rig was assembled, and it was operated and monitored successfully with manual control in operational tests (Pitkänen 2016). A potential test procedure for fatigue tests was defined, and the final commission tests are in the starting phase.

Close collaboration with international classification society.

Figure 6. **Large-size planetary gear**

Modeling and simulation of gears

Modeling and simulation of the gear pair has an important role as a part of the design process, to estimate the stresses, deformations, and damage risks in various operating conditions. The high performance and long life of gears requires that gear flank surfaces create an optimal contact pattern along the line of action, meaning in all gear flank locations that occur during gear meshing. In general, the contact pattern should cover a large contact area to minimize the maximum pressure, but at the same time it must be located within the flank surface area to avoid edge contacts. Unfavorable gear contact conditions may have many reasons, such as shaft misalignment, deformations, and inaccuracies in manufacture and assembly. A poor contact pattern may cause a major life reduction, as well as vibration and noise. The proper contact pattern is the key issue in the gear design process and it is typically controlled with local tooth flank surface modifications, for example, to compensate for gear, shaft, and gearbox deformations in certain loading conditions. The finite element method (FEM) is typically used for these calculations. However, localized gear pair contact moves along the line of action, raising the need for a very dense FE mesh over the whole gear flank. This usually means a long calculation time. The challenge is to reduce the number of elements so that the accuracy is preserved.

The main purpose of this task was to develop an effective parameterized model for the analysis of stresses in gear contact and the gear root. In addition, the gear contact pattern along the line of action was analyzed by taking into account the multiple tooth contacts and tooth flank modifications. The multiple tooth contacts mean that in the case of spur gears, two contacts may occur at the same time and the load sharing between them can be solved numerically along the line of action. A local adaptive FE mesh approach was developed, in which a dense FE mesh zone around the contact point moves along the line of action to speed up the computation. An accurate surface profile of the gear tooth flank was created by simulating the gear manufacture, meaning the hobbing process. This provides a possibility to use realistic gear geometry, which can be modified flexibly. Illustrations of the adaptive FE mesh gear geometry and the computed contact pressure distribution in one mesh location are shown in Figures 7 and 8.

Efficient modeling solution using an adaptive dense FE mesh zone.

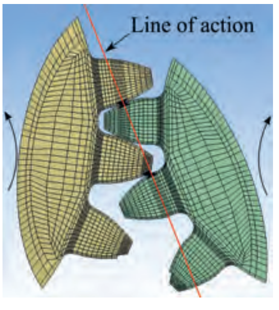

Figure 7. Illustration of the moving dense part of the FE mesh with multiple tooth contacts

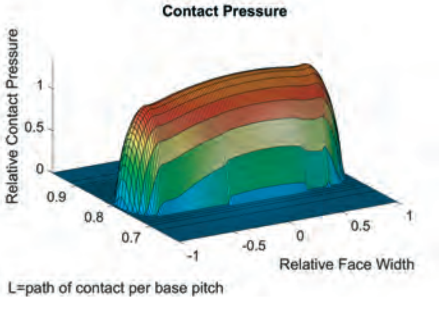

Figure 8. Contact pressure distribution with tooth flank modifications and misalignment

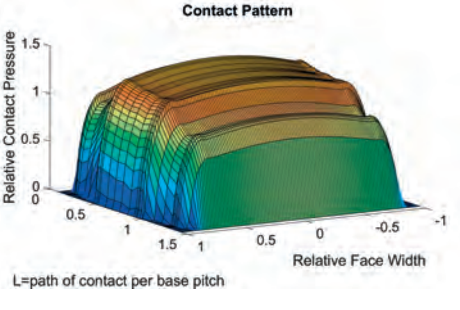

Figure 9. The contact pressure pattern

The developed FE mesh approach was validated successfully against analytical Hertzian theory using a 2D contact of cylindrical bodies (Lahtivirta & Lehtovaara 2016). It was found that the parameterization of the model was important because the necessary mesh density is case dependent. Tooth dimensions and loading affect the selection of the FE mesh parameters. For example, different loading conditions may not be properly solved with the same mesh density, because the contact area between the pinion and the gear is dependent on a normal load. In addition, it was found that the maximum pressure converged with high precision already with a low number of elements in contact, but a fairly dense FE mesh is needed to define the exact position of maximum shear stress and the contact width. The gear model maximum contact pressures and tooth root stresses were also successfully compared to the corresponding results based on gear standard ISO 6336, and to the analytical approach based on Weber and Banaschek in basic loading cases, that is, without flank modifications and shaft misalignment. The parameterized gear simulation model enables optimization of the contact pattern and tooth root shape to maximize the load-carrying capacity of the gear pair. The contact pattern consists of maximum pressure values at different locations of tooth engagement, meaning along the line of action as shown in Figure 9.

The parameterized gear simulation model enables optimization of the contact pattern and tooth root shape to maximize the load carrying capacity of the gear pair.

Conclusions

The research work introduced in this project showed high potential results and active co-operation between academic research and industrial partners. The test methods were established to carry out tooth root and gear contact fatigue tests based on the guidelines of the international classification society, and corresponding preliminary S-N curves were achieved. The obtained results indicated significant potential for improving gear fatigue life and torque density by using new types of case hardened steel and surface treatments. Online particle monitoring from oil was successfully applied to provide deeper understanding of macropitting behavior. In addition, a parameterized gear model was developed, which enables optimization of the contact pattern to maximize the load-carrying capacity of spur gear pair.

Company impact

"Material technology plays a key role in improving the competitiveness of wind turbine gearboxes. Technology projects like GeFa and NoCMa are crucial for Moventas to achieve market needs for lowering the LCoE (levelized cost of energy) of wind energy."

Jukka Elfström, *manager, research and verification, Moventas Gears Oy*

"Participation in the DIMECC / BSA / GEFA project has been the framework to get scientific guidance in starting to work with ATA's recent investment, the large-scale bevel gear test rig. In addition to scientific guidance from TUT and the promising results from the gear modeling and laboratory-scale experiments, it has also been a unique opportunity to cooperate with the Finnish industrial companies Moventas and Ovako. Before this project, we have had a limited commercial connection, and no knowledge of each other's research activities. By now, we have found a lot of common interest and synergy in research activities, and have also increased commercial cooperation."

Gabor Szanti, *engineering and development manager, ATA Gears Ltd*

Outlook

There is a need to continue research and development processes related to gear performance, and especially its torque density to decrease the masses and dimensions of structures. This needs further development and the implementation of case hardened gears with higher fatigue strength, as well as various kinds of surface treatments such as thin coatings. Even the updated test methods are available, and preliminary S-N curves were achieved, more extensive fatigue test series should be carried out to be able to convince the classification societies and to obtain their permission to use higher fatigue strength values than stated in conventional standards. The continuous improvements in the torque density of studied gears has increased test loadings, and the test rigs themselves should be upgraded to handle higher load ratings. The other important issues to be studied in more detail are other gear flank failure types, such as micropitting. The development of a gear model needs to be continued to take into account the gear excitation and mixed lubrication conditions, as well as surface topography issues and residual stresses. To bring the obtained results and gear performance concepts to a real product level, these solutions should be tested in large-scale proto gear boxes using a controlled test program. This will also give valuable feedback on how to scale up the lab-scale results.

Further information

KEY PUBLICATIONS:

Aaltio, H-R. 2015. Grain size control in carburizing steel, MSc- thesis, Tampere University of Technology.

Kattelus J., Lehtovaara A., Miettinen J. 2016. Detection of gear pitting failure progression with on-line particle monitoring, Proc. of 17th Nordic Symposium on Tribology, Aulanko, Finland, June 14–17. Upgraded paper has been accepted to Tribology International.

Paattakainen, O., Elfström J., Kleemola, J., Soivio, K. 2017. Material technology plays a key role in improving torque density in wind turbine gearboxes. Conference for Wind Power Drives 2017, Aachen, Germany, March 7–8. (Conference presentation and proceedings).

Pitkänen, J. 2016. Commissioning of a large-scale bevel gear test rig, Master's thesis, Tampere University of Technology.

Lahtivirta J. & Lehtovaara A. 2016. Modelling of spur gear contact using a local adaptive finite element mesh, Finnish Journal of Tribology, 34(2016)1–2, pp. 43–56.

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PARTICIPANTS:

ATA Gears Ltd, Moventas Gears Oy and Ovako Imatra Oy Ab has been involved in this sub-project together with research groups (Tribology and Machine Elements and Tampere Wear Center) from Tampere University of Technology (TUT).

Henri Järvinen, Pasi Peura/Tampere University of Technology
Martti Järvenpää/SSAB Europe Oy

Hot-dip galvanized press hardening steels

Summary of the project's motivation and achievements

Current technology

In recent years, the automotive industry has faced an increasing demand to reduce CO_2 emissions and simultaneously improve the safety performance of passenger cars. Currently, all automotive OEMs are changing the steel materials used in the safety components of the car body-in-white (Figure 1), meaning that the present multi-phase steels are being replaced by press-hardening steels (PHS). Press hardening, in turn, is a relatively new manufacturing method in which a steel blank is formed at a high temperature and subsequently quenched in a die.

Figure 1. **Press-hardening technology is increasingly used to manufacture high-strength safety components for the car body**

More importantly, there is a constant demand for PHS with a protective and corrosion-resistant coating, providing improved material properties. Automotive manufacturers are seeking a replacement for the current material technology, AlSi-coated 22MnB5 steel, due to both technical and commercial reasons. Steels with a zinc-based coating, Zn or ZnFe coating, have shown potential and can provide cathodic corrosion protection at ambient temperatures. ZnFe, zinc-iron alloy coating, is also called a

Galvannealed coating within the steel industry. Unfortunately, zinc-coated steels are associated with certain challenges, such as the risk of liquid metal embrittlement (LME) induced cracking during hot deformation. However, LME can be avoided by eliminating the liquid zinc at hot forming temperatures. Therefore, a ZnFe coating with an initial iron content of 8–12% provides a better starting point for the direct press-hardening process.

Car manufacturers require that the material producer can provide both scientific and industrial information regarding the steel and coating, meaning that guidelines on processing the material for optimum performance are required. Currently, the behavior of ZnFe-coated boron steels in the direct press-hardening process is not clearly known. Therefore, more research is needed to supplement the understanding of the material behavior and suitable process parameters, and finally to launch zinc-coated products on the market.

Need for greater strength and enhanced corrosion protection

The most widely used press hardened steel is boron-alloyed grade 22MnB5, providing a yield strength of 1100 MPa and a tensile strength of about 1500 MPa. The use of 22MnB5 has strongly increased and is still projected to grow. Customers require strength levels of up to 2000 MPa already now, but at the moment, the steel industry has not been able to provide a properly working option in that strength class. At higher strength levels, retaining adequate toughness is particularly challenging. In addition, bake hardening, occurring during the paint baking of automotive components, affects the final mechanical properties of PHS. The paint-baking process is typically simulated with a simple heat-treatment of 170°C/20 min carried out according to the EN 10325-2006 standard. Understanding of the bake-hardening effect is required, especially when the properties of 2000 MPa grade PHS are to be optimized. Finally, developing a zinc-coated press-hardening boron steel with a tensile strength of 2000 MPa is an ambitious task for this project.

The automotive industry looks for high-strength press-hardening steels with enhanced corrosion resistance.

The motivation of the sub-project can be divided into three tasks:

1) Understand the behavior of ZnFe-coated 22MnB5 steel in the direct press-hardening process in order to manufacture material to its best performance. This includes minimized cracking in hot forming and adequate corrosion protection capacity, meaning the proper phase structure and zinc content of the press hardened coating. Investigations on the relationships between process parameters and material performance are needed to achieve this specific target.

2) Develop a new generation ZnFe-coated PHS grade with a tensile strength of over 2000 MPa. This requires comprehensive understanding of the relationships between microstructure and mechanical properties. In addition, the bake-hardening effect of PHS needs to be taken into account.

3) Evaluate the joinability parameters for resistance, arc, and laser welding, followed by joint property evaluation. Evaluate the hydrogen embrittlement resistance of steels, formed components, and joints.

Remarkable achievements

All of the above tasks have been under extensive investigation, and remarkable results have been achieved. The achievements are going to be used to enhance the uptake of PHS grades in the automotive industry.

The major achievements are summarized below:

1a) Proper **annealing parameters** (austenitization temperature, and time) during the direct press-hardening process have been obtained for ZnFe-coated 22MnB5 steel. The result is used to avoid LME-induced cracking in hot deformation. The results cover a range of initial coating weights: 40/40, 50/50, 70/70, and 80/80 g/m^2. The properly annealed coating consists of α-Fe(Zn) phase and contains ~30 wt% zinc on average.

1b) Understanding of the relationships between initial material properties, process parameters, and undesired micro-cracking in **hot-press forming** have been significantly increased. We found that both the higher zinc content of the annealed coating and the higher initial coating weight increase the susceptibility to micro-cracking. It has also been discovered that novel modifications to both processes and materials are most likely needed to fully eliminate micro-cracking, especially in the case of demanding hot-forming geometries. This issue is currently under investigation.

2a) Understanding of **the effect of initial microstructure** on the final mechanical properties of press hardened 22MnB5 steels has been obtained. An optimal initial microstructure of 22MnB5 steel with respect to the final mechanical properties after press hardening was found. This information is in use in SSAB's steel production and will also be used in the near future as an essential part of the development process of a new generation of PHS grades. On a general level, we discovered the development of microstructures and grain-size effects in the direct press-hardening process of 22MnB5 steel. Understanding of the high strain-rate behavior of martensitic 22MnB5 steel has also been obtained.

2b) Understanding of the **bake-hardening** effect of 22MnB5 steel has been achieved. Investigations on steels with higher carbon content are currently ongoing. The information on the bake-hardening effect of martensitic steels will also support the development of a novel 2000 MPa PHS grade.

2c) Investigations on the mechanical properties and press hardenability of the current 34MnB5 grades have enabled the design of novel chemical compositions for upcoming studies. The properties and behavior of these grades are used as references during the development process. The **new alloys** will be used mainly to investigate the effect of micro-alloying elements B, Ti, and V, as well as the effect of alloying elements Mn and Mo on the properties of 2000 MPa grade PHS.

3) Susceptibility to hydrogen embrittlement, joinability parameters, and determination of joint mechanical properties for new coatings and steel grades were investigated. Guidelines were created for transportation and storage to avoid hydrogen cracking. Resistance spot and laser welding are done, but more trials are needed and ongoing.

Key results and impacts

Annealing parameters for coated PHS

It has been observed that a precisely defined process window is needed to produce zinc-coated PHS successfully. It was discovered that liquid metal embrittlement (LME) induced cracking can be avoided with proper annealing. After that, the coating consists of α–Fe(Zn) phase and contains ~30 wt% zinc on average. According to the literature, a zinc-iron alloy coating of this type can provide cathodic corrosion protection with the composition mentioned above. Figure 2a presents the typical structures of press hardened ZnFe coatings on 22MnB5 steel as a result of a too short (undesired) and proper annealing procedure (desired), while Figure 2b shows the observed relationships between the zinc content of the coating and an annealing time at 900°C.

Successful manufacture of zinc-coated PHS requires a precisely defined process window.

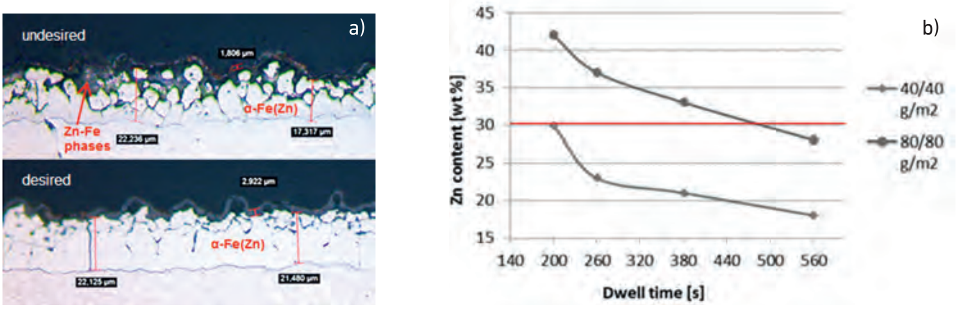

Figure 2. a) Optical micrographs of press hardened ZnFe coatings; b) The average zinc content of press hardened ZnFe coating as a function of annealing time at 900°C

The obtained results are important steps when determining suitable process parameters for ZnFe-coated steels in the direct press-hardening process. In addition, the results limit the process window from the point of view of further investigation. See the associated publication [1] for more information.

Hot-press forming

The hot-press forming experiments indicated that another type of cracking, namely micro-cracking, can still occur despite the prior elimination of liquid phases during annealing. Figure 3a presents the correlation between the crack depth and the annealing time at 900°C, while Figure 3b illustrates the nature of cracking observed in hot-formed test parts.

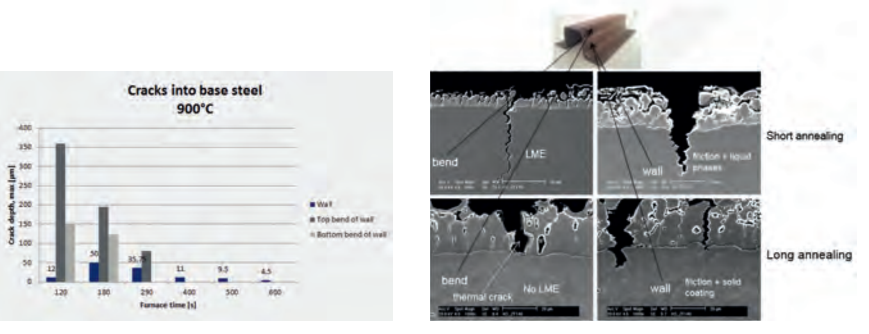

Figure 3. **a) Correlation between the crack depth and annealing time at 900°C; b) Illustration of LME-induced cracking and micro-cracking on the bend and wall sections of the hot-formed test part**

Non-conventional hot-forming temperatures are required to eliminate micro-cracks.

The results have also indicated that non-conventional hot-forming temperatures are most likely required in order to enhance the quality of the coated components. Experiments at different hot-forming temperatures are currently ongoing at Tampere University of Technology.

The effect of the initial microstructure

It was found that the strength and uniform elongation values of press hardened 22MnB5 steel depend on the initial microstructure. The initial microstructure has a significant role in determining the parent austenite grain size (PAGS), which in turn determines the morphology of the transformed martensite. The tensile properties of the press hardened materials were almost strain rate-independent in the studied strain rate range.

Understanding of the grain size effects and the role of initial microstructure allows to optimize properties of PHS.

The obtained results can be used to optimize the properties of PHS. The results are used to optimize the steel properties in SSAB's production.

In addition, the revealed connection between PAGS and the final steel properties should be taken into account in the development process of the new press-hardening steel grades for the automotive industry. The study also showed that PAGS can be reliably used to explain the differences in the mechanical properties among PHS with the same chemical composition. See the associated publication [2] for more information.

Bake-hardening effect

It was found that a typical paint-baking treatment (170°C/20 min) has a significant effect on the mechanical properties of PHS. The results show that smaller PAGS leads to a stronger bake-hardening effect in terms of yield strength, but PAGS had no clear effect on the tensile strength of bake hardened PHS steels. Uniform elongation showed a minor decrease as a result of the baking. Figure 4 shows a correlation between PAGS and the obtained increase in yield strength.

Paint baking influences the in-service properties of PHS.

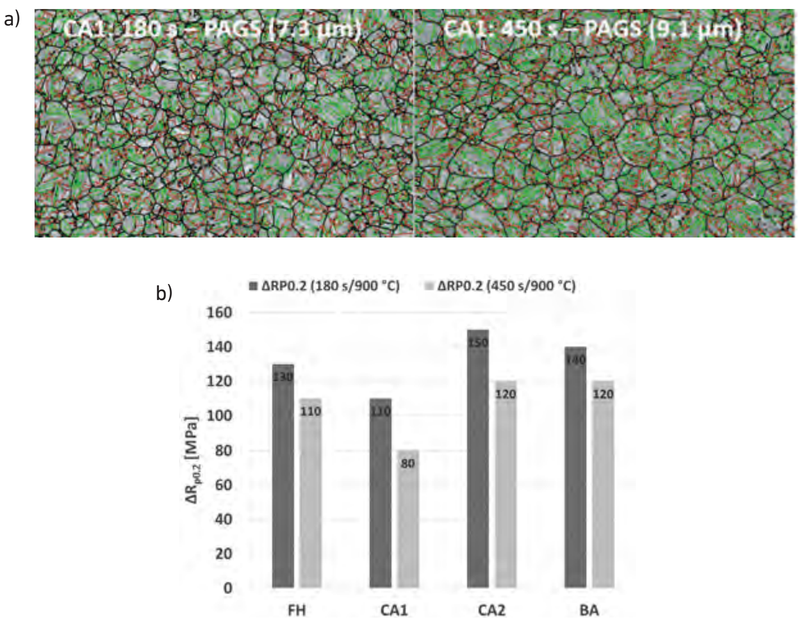

Figure 4. **a) Examples of the reconstructed parent austenite grain boundary maps (boundaries shown with black lines) and measured PAGS for steel CA1; b) Observed correlation between parent austenite grain size (PAGS) of the investigated 22MnB5 steels (FH, CA1, CA2, and BA) and increase in yield strength after the baking treatment. The shorter austenitization time (180 s) resulted naturally in smaller PAGS and higher ΔRp0.2 as a result of bake hardening**

The next publication [3] addressing the bake-hardening effect of PHS is soon to be submitted.

New alloys

The development process of a new PHS steel grade was continued with the preliminary press-hardening experiments carried out for two ZnFe-coated 34MnB5 steel grades with a tensile strength of approximately 2000 MPa after quenching. Both flat-die and hot-forming experiments were involved in the testing procedures. Microstructural development, final mechanical properties, and press hardenability of ZnFe-coated PHS have been studied. The experiments are still ongoing at TUT and SSAB. However, the preliminary results have been used to design new steel compositions for further investigation in a constant collaboration between TUT and SSAB.

Research on current PHS grades has enabled the design of new, higher-strength grades.

The design of novel chemical compositions was performed in collaboration between TUT and SSAB. The planning was supported by the preliminary results regarding two 34MnB5 grades and a literature survey. The effect of micro-alloying elements Ti, V, and B, as well as alloying elements Mn and Mo, will be mainly investigated. Lab castings were ordered from Swerea KIMABB in December 2016. The lab steels will be hot and cold rolled at the University of Oulu. The sample material will be used in press-hardening experiments planned to start at the beginning of 2017. The upcoming results will provide important information for the development of a novel 2000 MPa PHS grade.

Hydrogen embrittlement

Measurements and analyses have been done using the scientific and technical experience collected at Aalto University on hydrogen embrittlement. The thermal desorption spectroscopy technique, microscopic observations, fractography, and tensile testing under continuous electrochemical hydrogen charging were used in this work. Samples from the plates with different Zn-based coatings and without coating, hat-profile samples, and tensile samples were supplied by SSAB (Hämeenlinna). The role of non-metallic inclusions in hydrogen-induced fracture was analyzed. All the studied steels were found to be sensitive to hydrogen embrittlement. Average hydrogen concentration is calculated using thermal desorption spectroscopy measurements. Hydrogen sensitivities of the studied steels were estimated for the materials after tensile testing. The influence of hydrogen on the properties of high-strength boron steels was compared with regard to the parameters for heat treatment and the coating of the steels [4].

PHS are sensitive to hydrogen embrittlement and this needs to be considered in manufacturing routines.

Company impact

“One of SSAB’s strategic focus areas is the automotive customer segment, where we have set a target to double sales within the next 10 years. Even though vehicle sales are increasing globally, steel weight per vehicle will reduce. However, driven by light weighting and safety trends, the use of advanced high-strength steel (AHSS) in the automotive segment is expected to increase significantly in the future. This project not only supports our high-strength steels strategy, but can also contribute to the performance of the entire company.”

Martti Järvenpää,
head of product development, SSAB Europe Hämeenlinna

The results support SSAB’s high-strength steel strategy and can contribute to the performance of the entire company.

Further information

KEY PUBLICATIONS:

H. Järvinen, S. Järn, E. Lepikko, M. Järvenpää, P. Peura, ZnFe Coated 22MnB5 Steels in Direct Press Hardening: The Relationships between Coating Structure and Process Parameters, Key Engineering Materials, Vol. 674, 2016, pp. 331–336.

H. Järvinen, M. Isakov, T. Nyyssönen, M. Järvenpää, P. Peura, The effect of initial microstructure on the final properties of press hardened 22MnB5 steels, Materials Science and Engineering: A, Vol. 676, 2016, pp. 109–120.

H. Järvinen, M. Järvenpää, P. Peura, Bake hardening behavior of press hardened martensitic steels: effects of parent austenite grain size and carbon content. To be submitted in 4/2017.

O. Todoshchenko, H. Hänninen, Studies of Hydrogen Embrittlement, Technical report, Aalto University.

H. Järvinen, P. Peura, M. Järvenpää, Muottikarkaistavien teräslaatujen kehityslinjat, Ohutlevy-lehti, 1/2015.

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Jyrki Kesti/Ruukki Construction
Jussi Minkkinen/SSAB

Ductility requirements for new constructional high-strength steel grades

Summary of the project's motivation and achievements

The use of high-strength steels in civil engineering has been mainly limited to weight minimized applications, such as vehicle bodies, and lifting and hoisting devices. Occasionally they are also used in statically loaded structures, as in drilling rigs, pipelines, heavy industrial plants, bridges, and long span trusses. Savings in weight reduce the carbon footprint in manufacture and transport. The outstanding properties of these steels could be utilized more widely in the construction industry, if the design codes were up to date.

Eurocode rules cover structural steel grades up to S700, but not higher. Moreover, the relatively high ductility requirements of ultimate-to-yield strength ratio ($f_u/f_y \geq 1.05$), elongation at failure ($A5 \geq 10\%$), and uniform strain ($\varepsilon_u \geq 15 f_y/E$, where E is the modulus of elasticity of the material) form a barrier to the use of many high strength steels. Therefore, complementary to experimental results, improved numerical methods are needed for the assessment of the required material ductility in different structural details.

Figure1. High-strength steels are used typically in demanding structural applications

The ductility of steel is important, especially in the details with holes and notches, where the stress concentration develops under the load (see Figure 1), and it has to be assessed carefully in order to prevent the failure of the material. For this purpose, numerical FEM methods are able to deliver highly accurate predictions of the behavior of particular structural details.

The VILMA project was planned to establish **a "virtual testing" platform for designers** to verify the performance of the structural details subjected to various loadings that cause stress concentration and diffuse necking. Based on this platform, VTT Technical Research Centre of Finland has developed, together with Ruukki Construction and SSAB Europe, acceptance criteria for new constructional high-strength steel grades. A new method of defining the requirements for material ductility parameters was developed. This method was applied to the verification of local failure of structural parts with holes and round notches.

A virtual testing platform for designers to verify the performance of structural details under loading.

Key results and impacts

Our goal was to propose the evaluation of one selected ductility criterion (elongation at failure $A5$) for a given range of the remaining parameters (uniform elongation ε_u, and ultimate-to-yield strength ratio f_u/f_y) that extend the current Eurocode requirements. The basic assumption was that the structural members have to sustain design loads without ductile failure. Then the material has to tolerate plastic strains in localized areas around holes and notches.

The proposed method relies on a standard material coupon test and two numerical models, one of the selected structural detail and one of the coupon itself (see Figure 3). The minimum required elongation at failure can be predicted by comparing the maximum equivalent plastic strains in both models (Figure 2). This simplification disregards the role of hydrostatic stress in the material, and therefore it is conservative as long as the fracture strain decreases with increasing triaxiality, and triaxiality at failure is higher in plain coupons than in the details with stress concentration.

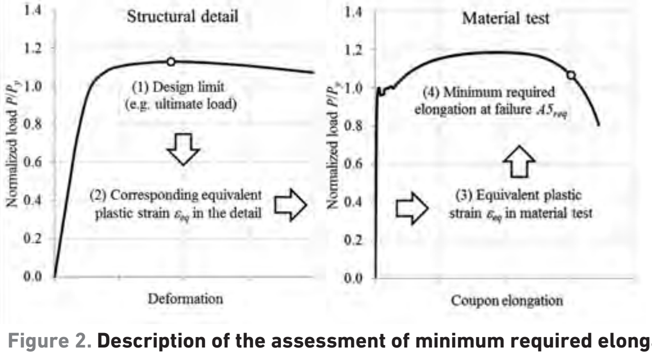

Figure 2. Description of the assessment of minimum required elongation at failure

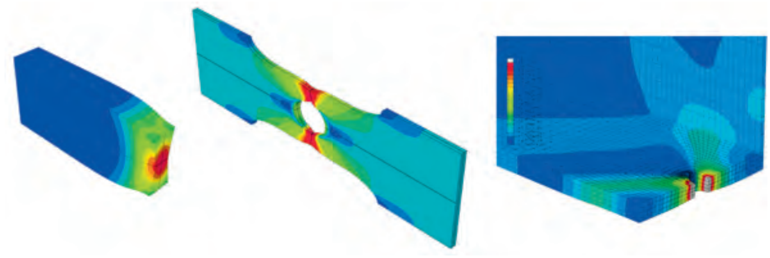

Figure3. **Example of numerical models of coupon (left) and two details (middle and right)**

New term “necking capacity” to describe elongation to failure.

One of the important findings is that the minimum required elongation at failure $A5$ is related to the material's uniform elongation ε_u rather than to a fixed value, and therefore **we have established the new term “necking capacity”** of the material, being $A5 - \varepsilon_u$. This capacity was below 6% in our studied details.

Table 1. **Ductility limits based on the numeral study**

	Eurocode limits	Proposed limits
Elongation at failure	$A5 \geq 10\%$	$A5 \geq \varepsilon_u + 6\%$
Ultimate-to-yield strength ratio	$f_u/f_y \geq 1.05$	$f_u/f_y \geq 1+ \varepsilon_u/2.55$
Uniform elongation	$\varepsilon_u \geq 15 f_y /E$	$\varepsilon_u \geq 6 f_y /E$

As can be seen from Table 1, the 6% necking capacity $A5 - \varepsilon_u$ can also be expressed in a form compatible with Eurocode 3. The ultimate-to-yield strength ratio limit (f_u/f_y) in Table 1 is based on the calculation instability of the FEM solver and can be improved by more accurate models. The requirement of uniform elongation to be proportional to the yield strength is probably the most controversial of the current ductility limits, and it does not exist in American or Australian codes. However, we have confirmed that in order to reach the rotational capacity of Class 1 cross-sections in bending, this proportionality is needed, although it can be lowered to $6 f_y /E$.

Using the proposed limits, the new grade S960 can be acceptable with the following minimum ductility: $\varepsilon_u \geq 2.8\%$, $f_u/f_y \geq 1.02$ and $A5 \geq 8.8\%$. **All of these proposed limits are easier to satisfy than the current requirements** $(\varepsilon_u \geq 6.9\%$, $f_u/f_y \geq 1.05$ and $A5 \geq 10\%)$.

The proposed ductility limits are based on virtual testing of real details with a simplified tri-linear true stress-strain material model; an elastic stage up to f_y, a strain-hardening stage up to f_u, and an ideal plastic stage after f_u. The results for standard tension coupons, tension specimens, and beams were achieved by fully automated numerical FEM procedures developed at VTT. The study with about 200 material models covered the f_u/f_y ratio up to 1.5, ε_u from 2% to 50% and members with a central hole or side notch. The method was validated by experiments with the central hole in tension specimens provided by Ruukki Construction and SSAB.

We would like to thank Ruukki Construction and SSAB Europe for the experimental results and support throughout the project.

Company impact

"The development of high-strength steels (HSS) has been accelerated in recent years, and many studies demonstrate the cost and environmental benefits of HSS in structures regarding material costs, fabrication costs, and CO_2 equivalent. However, the use of HSS in the construction industry is very low due to conservative design rules in current design standards. The results of this research are very promising in extending the use of HSS to the construction industry and can be directly utilized in standardization work."

Jyrki Kesti, *Ruukki Construction, and* ***Jussi Minkkinen,*** *SSAB Europe*

Further information

KEY PUBLICATIONS:

Hradil P., Fülöp L., Talja A. and Kurkela J. 2017. Experiences from numerical modelling of details with ductile failure, Research Report VTT-R-01177-17. Espoo: VTT Technical Research Centre of Finland, Ltd.

Hradil P., Fülöp L., Talja A. and Ongelin P. 2016. Ductility requirements for structural details with stress concentration and diffuse necking. In: The International Colloquium on Stability and Ductility of Steel Structures – SDSS 2016, Timisoara: Universitatea Politehnica Timișoara.

Hradil P. and Talja A. 2015. True stress-strain relationship for finite element simulations of structural details under diffuse necking. In: Nordic Steel Construction Conference 2015, Tampere: Tampere University of Technology, 229–230.

Hradil, P. and Talja, A. 2016. Ductility limits of high strength steels, Research Report VTT-R-04741-16. Espoo: VTT Technical Research Centre of Finland, Ltd.

Talja, A., Kurkela, J. and Hradil, P. 2015. FEM based virtual testing of HSS beams with flange holes, Research Report VTT-R-02326-15. Espoo: VTT Technical Research Centre of Finland, Ltd.

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Optimization, prediction, and design guidelines for the improved wear life of novel steels and metallic multimaterials

Background

New wear-resistant materials offer new possibilities and business opportunities for industry working with heavy abrasive and impact wear, the transfer of particulate solid or slurry materials, and the crushing of minerals. The development of wear-resistant materials, however, is challenging and requires a lot of research, including basic materials characterization, laboratory wear testing, and in-service trials. One of the greatest challenges is the multitude of conditions that the products face in in-service conditions.

The simulation of in-service wear environments on a laboratory scale is challenging. In the planning of the test procedures, the effect of many variables, such as the contact mode, loading energy, abrasive properties, and environment on the active wear mechanisms and the resulting wear rate must be carefully taken into consideration. The interpretation of the laboratory test results is normally easier, and the repeatability of the tests is better than that of complex and expensive in-service tests. On the other hand, the utilization of the field test results is usually quite straightforward, and the tests easily reveal the possible problems in the design or selection of materials. Thus, to select the best possible testing approach for each case, it is important to have a good understanding of the relevance of the laboratory wear tests in predicting the in-service performance of materials in high-stress wear conditions. This knowledge also makes the utilization of the laboratory test results more straightforward in industry.

The development of wear-resistant materials requires solid understanding of wear phenomena.

Although the behavior of materials in various wear conditions is extremely complex, the systematic development of increasingly better materials for different types of wear is possible, when the basic understanding of the underlying phenomena is solid. One remedy to these problems is to use modeling to describe, explain, and predict these phenomena and their consequences. However, modeling needs accurate material data and material models to produce useful and reliable results, and therefore, sophisticated experimental techniques must be utilized to obtain this information and to validate the modeling and simulation results.

As the mining and construction sectors are becoming increasingly important for the Finnish economy, and international competition is constantly tightening, more efficient and reliable machinery, such as crushers and other auxiliary equipment, must also be developed. As an example, the jaw crusher system and the whole action of the crushing process need to be studied in terms of dynamics, kinetic friction, and vibrational effects. This type of research is totally new and aims to develop the next generation of crushers, relying on a deep understanding of the jaw crusher dynamics in the crushing action, based on high-level simulation and dynamic calculation of the motion of the steel structures. The dynamic simulation will enable identification of the possible risks in the structures regarding, for example, fatigue and resonance, and will provide information for the development of more efficient next-generation crushers.

Solutions

To find the solutions to the problems and challenges described above, the project was divided into the following tasks:

1. Optimization of the compositions and properties of steel castings, special steels and composites (e.g., hard metals), and metallic multimaterials for different wear-related applications

The properties of materials to resist wear can be optimized by carefully characterizing their basic properties, by relating these properties to their microstructures, and by conducting intelligently designed wear tests that measure the desired properties for different applications and/or conditions.

2. Prediction of the wear life of materials in various conditions

Prediction of the behavior of new wear-resistant materials can be based on the direct results from the wear tests, phenomenological modeling of the wear behavior, and multiscale constitutive modeling of wear in the given circumstances. Moreover, it is essential to acquire a better understanding of the relevance of the laboratory wear tests in predicting the in-service performance of materials in high-stress wear conditions, such as processing, crushing, hoisting, and hauling of rocks in various mining, excavation, and construction applications.

3. Creation of design guidelines and instructions for the use of the new materials developed in this project

Modeling solutions bridging the gap between fundamental material characteristics such as microstructure, accelerated laboratory-scale testing, and material performance in application in wear environments offer new tools for wear research. The examined in-service cases provide a basis and future methodologies for developing specific material solutions better suited for high-stress abrasion (cutting edge and jaw crusher cases) and erosion-corrosion (stirring tank case) wear environments.

4. Simulation of the dynamics of jaw crusher systems and crushing processes

The dynamic tools for the jaw crusher design can include modeling and measuring the vibrational effects and damping of the system, the creation of a user interface for simulation software, and simulation of the system behavior in various representative cases.

Results

Optimization of the compositions and properties of special steels and steel castings

"In the development of novel wearing steels, it is very important to have a good understanding of the wear mechanisms in in-service conditions. This project has given a lot of new information about wear in both laboratory and in-service conditions. It has been possible to test different things in the laboratory before going to the high-stress wear conditions in the mines," comments Pertti Mikkonen, product development manager, SSAB. SSAB's steel development during the BSA program is reported in detail in the chapter "Novel steel concepts". The Raex 400–500 HB product family in the thickness range 2–80 mm was further developed for improved impact strength and enhanced forming and welding properties, which even exceed the corresponding properties obtained by the traditional reheating and quenching process. Moreover, new protection steels Ramor 450 and 550, with good forming and protection properties, were developed and launched. For DQP steels, the process parameters were developed and their mechanical and microstructural properties studied. The abrasive and impact wear properties were studied both in laboratory and mining conditions. The examined in-service cases were the cutting edge of a mining loader bucket and the wear plates of a feed hopper. These cases were simulated experimentally in the laboratory and using numerical modeling, and the results were compared with the field tests. Moreover, the residual stresses formed in the cut edge layer of heavy steel plates during thermal cutting were linked to microstructural and temperature gradients in the steels (Jokiaho 2015).

Knowing the actual service conditions is essential in wear-resistant steel development.

The research carried out in the project has also brought up new, interesting information about the "old" wear materials such as white cast iron and Hadfield manganese steel. The abrasion wear resistance of white cast irons can be controlled primarily by adjusting the size, size distribution, and volume fraction of the carbide phase. The main physical property of white cast irons, correlating with their abrasion resistance, is hardness. In this project, hardened and stress-relieved, normalized, self-hardened, and as-cast states of high chromium white cast irons were evaluated. The correct size and orientation of the carbides were found to be crucial for the wear resistance of white cast irons in high-stress abrasive conditions. The different annealing procedures affected the formation of the carbide structure and its distribution, as well as the microstructure of the matrix. Moreover, the austenite-to-martensite ratio, together with a beneficial carbide structure, was found to have a strong effect on the abrasion wear resistance of WCI specimens. The columnar structure of thin and long carbides oriented perpendicular to the wear surface was found to provide the best abrasion resistance in crushing pin-on-disc tests with granite abrasive.

The microstructure, mechanical properties, and wear life of cast manganese steel wear parts for aggregate and mining crushers are the result of correctly defined and well-controlled production processes. The heat treatment, including the soaking treatment followed by efficient cooling, is the most important production step, ensuring the ductility and wear resistance of the steel. The required cooling rate in the water quench depends on the alloy, and is controlled by the water temperature and water flow around the component. The effect of the composition of the manganese steel and the efficiency of the water quench were evaluated by heat treating large test plates, the impact ductility of which was then measured, and materials for wear tests produced.

A modeling and simulation tool for water quenching of the manganese wear parts was also developed in the project. The tool can be used to calculate the water flow in a real quenching tank, and to predict the cooling of the wear part in the quench. Based on the obtained results, the water tank design, loading of the components on the supports, and water temperature control could be improved.

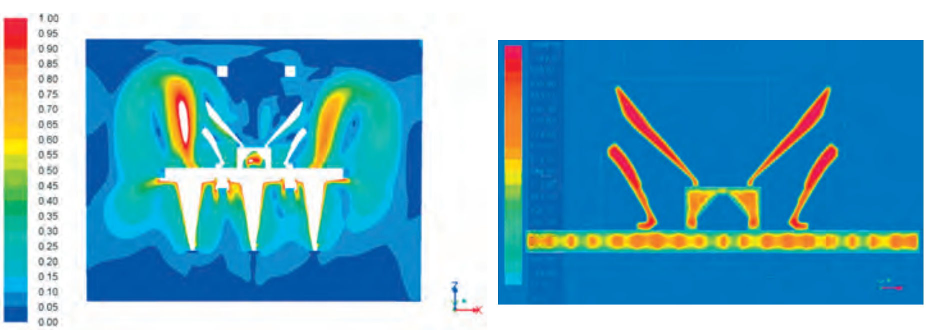

Figure 1. Modeling and simulation of water quenching: a) water flow model of a water tank at Metso Foundry, and b) simulation of cooling in a high wall thickness wear part

Wear testing of materials in various conditions

The wear environment has a significant role in the prediction of wear rates. Proper understanding of the variables and the effects that abrasives have on wear can affect the outcome of the material selection processes quite dramatically. Thus, the material selection based on laboratory wear tests needs test methods that simulate as well as possible the in-service conditions. Consequently, careful analysis of the relevance of the laboratory test methods is essential. Moreover, the effects of different rock species on the in-service performance of wear parts have to be taken into account in the material selection practices in the mineral processing industry. Detailed knowledge of the materials used in mining tools and wear parts, and how they perform in contact with different minerals, can improve the productivity of mining operations considerably. In this study, the variables affecting the frictional behavior of rock surfaces (Heino 2015) and the effect of rock types in high-stress abrasion tests (Valtonen 2016) were studied. The wear behavior in various in-service cases was simulated on laboratory scale using several application-oriented wear testing methods that produce high-stress abrasive or impact-abrasive conditions with large natural rock abrasives. Thus, they simulate the harsh conditions in mining and mineral processing. The wear behavior in the in-service cases was compared with the wear tested samples by analyzing the wear rates and by characterizing the wear surfaces and microstructures (Valtonen 2016, Vuorinen 2016a, Vuorinen 2016b). The importance of sufficient wear test duration was verified in a study of edge-concentrated wear in impact-abrasion testing (Ratia 2016a). Although most of the mass loss occurs at the edge parts of the samples in impeller-tumbler-type wear testing, the extent of the edge effect decreases with increasing test time.

Crushing of minerals consumes a very high amount of energy and the efficiency is quite poor. A laboratory-scale jaw crusher with uniform movement of the jaws, the Dual Pivoted Jaw Crusher (DPJC), was used to determine the relationship between wear and work (Terva 2016). The extent of wear was determined as the mass loss of the jaw plate specimens, while the amount of work (or consumed energy) was measured directly from the force and displacement of the instrumented jaw, which allowed work to accumulate only from the actual crushing events. The wear and work results obtained from the tests with different lateral movement of the jaws enable the determination of the wear coefficient K for each test configuration. A higher initial crushing speed decreases the amount of work needed to remove material from the specimen surface, that is, to cause wear in a DPJC crushing test.

As the pumping of slurry through pipelines is an increasingly more profitable alternative when transporting minerals or slurry away from mines or dredging sites, the technological boundaries in terms of wear resistance of the materials involved must be pushed forward. Currently, polymeric lining materials, such as rubbers or polyurethanes, have become a standard choice for combined wear and corrosion protection in slurry pipelines transporting minerals. However, such linings can be rather expensive and also quite sensitive to surface defects. In this project, slurry-pipe wear tests on high-strength steels and reference materials (polymers) were conducted with large and fine abrasives, various concentrations, and different sample angles, to reveal the differences in the behavior of the studied materials in slurry erosion conditions, and to find the best solutions for demanding applications. A slurry-pot tester, enabling the simulation of various wear conditions with different minerals, particle sizes, and abrasive concentrations, was used to simulate different industrial slurry applications (Ojala 2016a, Ojala 2016b, Ripoll). The results show that abrasion is the dominant wear mechanism already from a particle size of 2 mm, and that in demanding high-stress abrasive slurry erosion conditions, quenched wear-resistant steels can compete with polymers in wear resistance.

Wear and corrosion occurring in slurry pipeline and tank applications was further studied using novel slurry erosion-corrosion test equipment designed and built during the project. The equipment enables the separate study of erosion and corrosion, or their synergistic effects, which can greatly increase the material removal rates. The design principle was to use stationary specimens and parallel flow of slurry over the specimen surfaces. The test cavity was made of electrically insulating materials, which enables the use of a potentiostat to measure and control the electric potential of the stationary specimen. Figure 2a shows the open structure that enables the use of various particle sizes and compositions of the slurry. Thus, the system enables testing with slurry compositions close to the compositions used in actual applications.

Novel slurry erosion-corrosion test equipment was designed and built in the project.

a)

b)

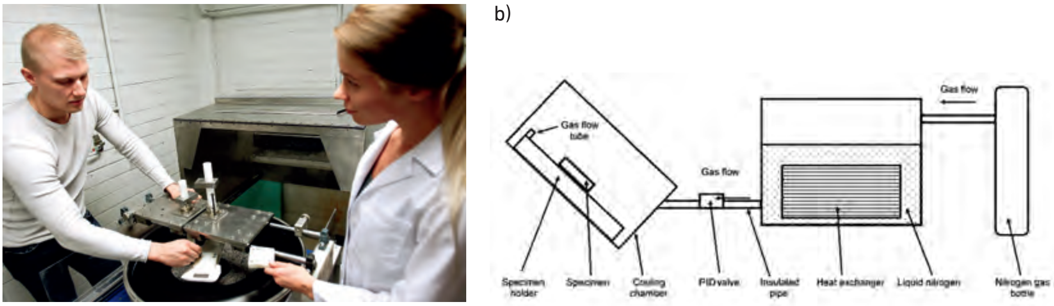

Figure 2. **a) Novel slurry erosion-corrosion test equipment, and b) schematic of the low-temperature system connected to the HVPI device (Ratia 2016b)**

Simple and repeatable testing systems are needed for the verification of the models for material mechanical behavior. The High Velocity Particle Impactor (HVPI) impact wear testing device was originally designed at Tampere Wear Center for single and multiple impacting of test materials at varying impact speeds and energies at room temperature. In the current study, dry, lubricated, and mechanically deformed surfaces of novel ultra-high-strength steels were impacted with HVPI (Ávalos del Río 2015). Moreover, temperatures corresponding to Arctic outdoor temperatures were used in the tests, aiming to assess the impact resistance of wear-resistant steels (Ratia 2016b). A controlled cooling system for the samples was also incorporated into the HVPI test environment (Fig. 2b). The LT-HVPI test system can be used to determine how low temperatures affect the impact behavior and microstructural changes caused by plastic deformation at relatively high impact energies. The obtained information can be used for the further development of wear-resistant steels for Arctic conditions.

Energy consumption and economic impact of friction and wear in the mining industry

Global energy consumption due to friction and wear in the mining industry was studied in this project. For the first time, wear was included in the more detailed calculations of tribological impact (Härkisaari 2015, Holmberg 2017). A large variety of mining equipment used for the extraction, haulage, and beneficiation of underground mining, surface mining, and mineral processing were analyzed with the following conclusions:

- Total energy consumption of global mining activities, including both mineral and rock mining, is estimated to be 6.2% of total global energy consumption. About 38% of the consumed energy in mineral mining (equal to 4.6 EJ annually on a global scale) is used to overcome friction. In addition, 2 EJ is used to remanufacture and replace worn-out parts and reserve spare parts and equipment needed due to wear failures. The largest energy-consuming mining actions are grinding (32%), haulage (24%), ventilation (9%), and digging (8%).
- Friction and wear annually result in 970 million tonnes of CO_2 emissions worldwide in mineral mining (2.7% of world CO_2 emissions).
- The estimated economic losses resulting from friction and wear in mineral mining are in total 210,000 million euros annually, distributed as 40% for overcoming friction, 27% for production of replacement parts and spare equipment, 26% for maintenance work, and 7% for lost production.
- By taking advantage of new technology for friction reduction and wear protection in mineral mining equipment, friction and wear losses

2.7% of the world's CO_2 emissions are due to the wear and friction in mineral mining.

could potentially be reduced by 15% in the short term (10 years) and by 30% in the long term (20 years). In the short term, this would annually amount to worldwide savings of 31,100 million euros, 280 TWh in energy consumption, and a CO_2 emission reduction of 145 million tonnes. In the long term, the annual benefit would be 62,200 million euros, 550 TWh in energy consumption, and a CO_2 emission reduction of 290 million tonnes.

The potential new remedies for reducing friction and wear in mining include the use of new materials, materials with improved strength and hardness properties, more effective surface treatments, high-performing surface coatings, new lubricants and lubricant additives, and new designs of moving parts and surfaces of, for example, liners, blades, plates, shields, shovels, jaws, chambers, tires, seals, bearings, gearboxes, engines, conveyor belts, pumps, fans, hoppers, and feeders.

Integrated computational materials engineering approach

An Integrated Computational Materials Engineering (ICME) approach was used to investigate the link between the material's wear behavior and its microstructure and material properties, to understand and quantify the material performance in the component and in larger-scale application conditions. ICME incorporates the beneficial features of experimental work, materials characterization, and multiscale modeling, which enables the verification of the component scale models based on the fine details of the microstructures.

Jaw crusher application model

Three in-service case models focusing on high-stress abrasive wear and erosion-corrosion phenomena were developed. First, the multiscale ICME approach was applied to a jaw crusher application in order to understand the mineral crushing events and their relationship to the wear behavior of high manganese austenitic steels, and to translate the realistic loading conditions to an appropriate microstructure scale. Crystal plasticity models were developed and verified by experiments and characterization, to accomplish the complex deformation and hardening response in different microstructures. The macroscopic crusher model showed that the strength of the crushed media has a significant effect on the energy consumed by the crusher, as well as on the loads faced by the material, which resulted in varying local deformation and hardening responses in the microstructure, with a notable effect on the wear resistance of the material. The modeling concept is exploitable as a design tool to improve crushing efficiency, end-product quality, and material performance. Virtual material tailoring can be adopted as part of the workflow, shown in Figure 3, to seek improvement in the material solu-

Virtual material tailoring can be integrated into the development processes of novel material solutions.

tion, for example by affecting the material's grain size and composition to enhance its strain hardening capability while optimizing ductility for impact-abrasive conditions.

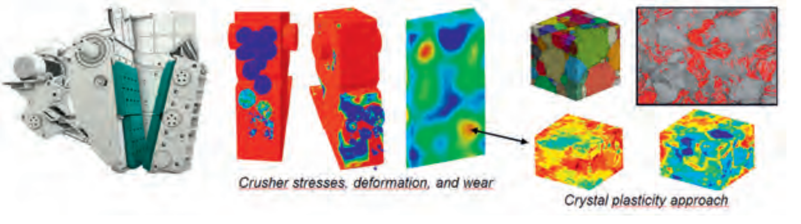

Figure 3. Multiscale modeling solution for the jaw crusher case

Cutting edge of mining loader bucket application model

A high-stress abrasion model was created for the cutting edge of a mining loader bucket application, focusing on wear-resistant martensitic steels. The macroscopic model was utilized to extract the surface loading history, the results especially indicating the wear-inducing response of specific contacts and their association with abrasive geometries. The abrasive character was found to be of significance, for example, with respect to surface roughness, which, in addition to the applied contact pressure, was found to deliver the greatest surface loading in the form of abrasive scratching, including both normal and significant surface shear loading. As in the first case, the wear environment is linked to microstructural crystal plasticity modeling, which enables the study of microstructure-scale material deformation, damage, and complex deformation phenomena deemed of interest, such as shear banding. Results demonstrating the modeling of the wear environment are presented in Figure 4.

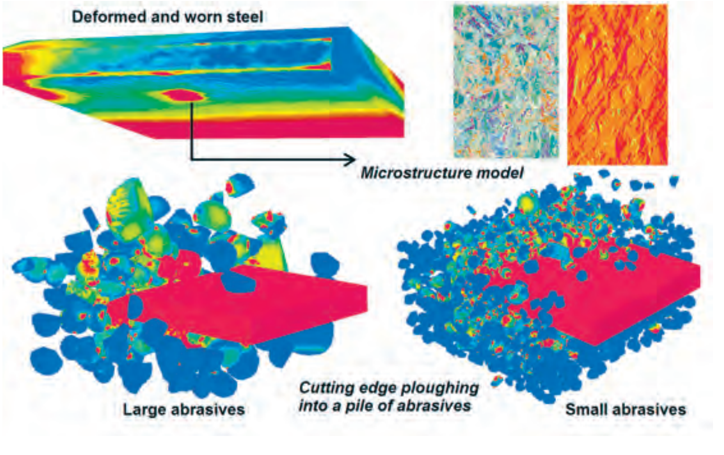

Figure 4. Multiscale modeling solution for the cutting edge case

Erosion-corrosion modeling framework

An erosion-corrosion modeling framework was developed, implemented, validated, and applied to both tribocorrosion and erosion-corrosion cases (Fig. 5). The model links the thermodynamic activity evaluation of the corroding environment, modeling of charge transfer reactions at the solution-metal interface, and the wear environment, and provides a capability for model updating as a result of mass loss during component life. Subsequently, the synergy between corrosion and mechanical wear can be evaluated as an outcome of modeling and the findings utilized, for example, in assessing the significance of the electrochemical system with respect to material selection and what primary parameters influence the performance of the material solution with respect to either corrosion, wear, or their interactions. The overall objective of linking complex operational environments to parameters of material (and microstructural) design and selection was reached, being the driving force behind all three examined cases. *"The combination of modeling and experimental testing is a powerful tool to enhance product development. In addition, this allows the generation of extensive datasets that cannot be reasonably obtained with only testing,"* states Mari Lindgren, development manager – Materials Technology, Outotec.

Combined experimental testing and modeling is a powerful tool to expedite product development.

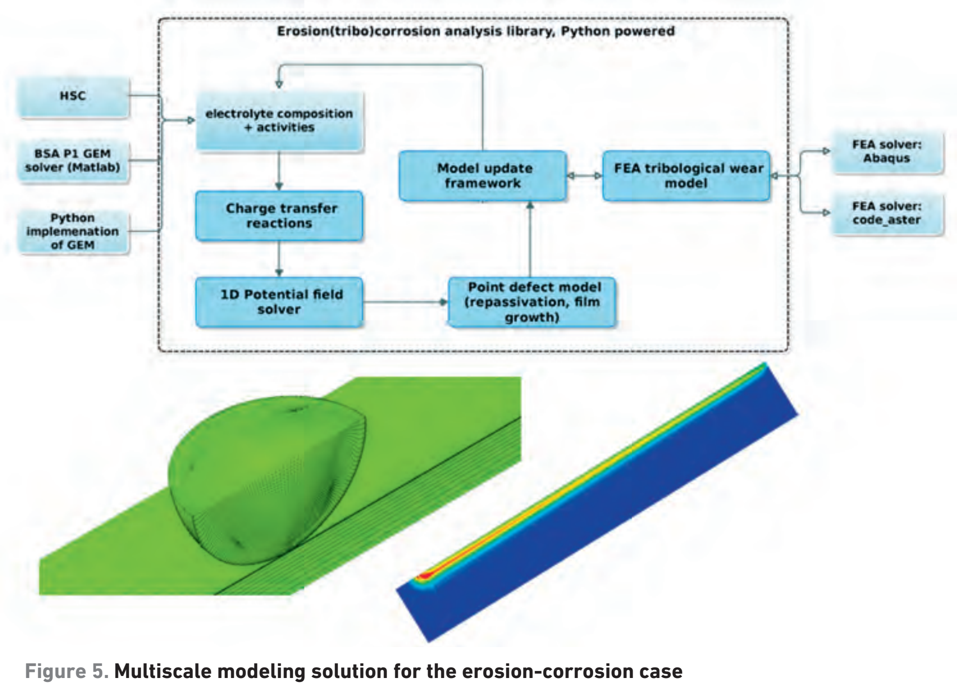

Figure 5. Multiscale modeling solution for the erosion-corrosion case

Dynamics of jaw crusher systems and crushing processes

The aim of this research was to create a mathematical simulation model and computer software to simulate the dynamic behavior of jaw crushers to provide design guidelines for industrial engineers. The focus was set especially on the reduction of support reaction forces of the jaw crusher by single or dual mass balancing and softer rubber pads, start and stop simulations, a better rubber pad model, basement error compensation by softer dampers, and a jaw crusher model to be used as a part of a HIL (hardware in-the-loop) model to make comparisons between simulated and measured experimental results. Moreover, an easy-to-use user interface for the simulation software, for practical engineering work, was pursued. The targets were achieved well, benefitting highly the practical jaw crusher design.

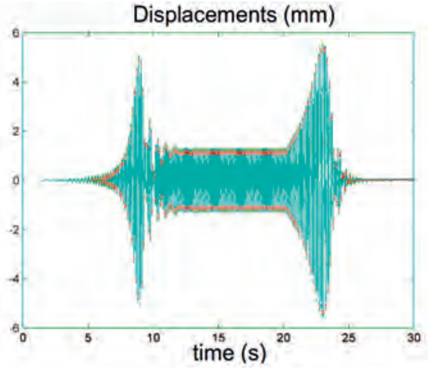

Figure 6. **Coulomb displacements of the rubber pads in resonance crossings of a jaw crusher during run-up and run-down ramps. Note the larger vibration amplitudes during run down**

The created dynamic simulation software can be used for a better design of the jaw crusher mechanism and its support. The computer tools for single and perfect first-order dual mass balancing of the pitman four-joint mechanism of a jaw crusher enable a reduction in the support reaction forces by up to 90%. This makes the crossing of the lowest resonance speed of the machine and basement error compensation by a softer support possible. The dual mass balancing method was successfully verified by measurements of a 10 kg miniature jaw crusher designed especially for this purpose. A reduced vibration level provides several benefits, such as lower stress and noise levels of the machine, an increased fatigue life, and material savings in the construction. The performed start and stop simulations showed that sudden stops or rapid decelerations of the jaw mechanism can create large and harmful forces in the supporting structures. Dynamic simulations for various rubber support cases were performed and analyzed, indicating that a significant reduction in the support reaction forces can be achieved. The developed nonlinear visco-elasto-plastic model, with viscoelastic Maxwell elements and frictional Coulomb elements, for the rubber pads of a jaw crusher, enable more accurate simulations of jaw crusher dynamics. Several run-up and run-down ramps of the C120 jaw crusher were simulated and compared to the corresponding HIL measurements with very good agreement. The resonance crossings displayed large vibration amplitudes with a resonance follow phenomenon during the run-down stage (see Figure 6).

As company cases, Metso's LT120 and NW120 jaw crushers were considered. The dynamic simulation software requires about 80 initial values for a jaw crusher to perform the simulation. These initial values were determined for both examined jaw crusher models, and several dynamic simulations were performed to study the support reaction forces, displacements, and velocities of the jaw crushers. It was found that one critical design aspect of the machine is the velocity of the drive unit, which must remain under a preset value.

The developed dynamic simulation and balancing software facilitates better vibration design, smaller displacements, smaller velocity of the drive unit, better balancing, lower stress levels, longer fatigue life, automatic analysis of steady states, ramps and support pads, thermal analysis of the rubber pads, a better rubber pad model, and more accurate simulation results. This creates a good starting point for manufacturing more competitive products. *"Deeper mathematical analysis and simulation of the dynamical behavior of the whole jaw crusher in the crushing action has brought up new tools for the design, and possibilities for further development of a more stable and energy-efficient crushing process,"* says senior materials research Marke Kallio, Metso Minerals.

New simulation tools for the design of jaw crushers.

Summary and outlook

A methodology combining experimental, modeling, and characterization techniques was introduced to systematically investigate the wear resistance of steels and to develop novel material solutions. Three in-service case studies on tailoring wear-resistant materials were carried out, based on the modeling of material-to-wear process interactions. The case studies provide a basis for developing specific material solutions better suited for the high-stress abrasion conditions in mining applications (cutting edge and jaw crusher use cases) and erosion-corrosion (stirring tank case) wear environments.

This project has considerably increased the understanding of the basic mechanisms of high-stress wear in the mining industry. Materials selection based on laboratory tests needs test methods that simulate as well as possible the in-service conditions. Consequently, careful analysis of the relevance of the laboratory test methods is essential. In this project, the wear behavior of various in-service cases was simulated on a laboratory scale, using several application-oriented wear-testing methods, some of which were developed during the project. All these test methods produce high-stress abrasive or impact-abrasive conditions with large natural rock abrasives, and thus simulate the harsh conditions in mining and mineral processing. Based on that, the material selection processes can now be conducted with significantly higher reliability. As part of the concrete outcomes of the project, several articles were published and three PhD theses were finalized: "Experimental and numerical studies on the abrasive and impact behavior of wear resistant steels," "The effect of compression and sliding movement on the wear resistance of steels and comminution in mineral crushing," and "Application oriented wear testing of wear resistant steels in mining and metallurgical industry".

The project results, merging wear environments with the design of steels, are globally novel and provide a basis for further innovations and accelerated development of improved wear-resistant materials and solutions. In addition, the tools enabling assessment and design against highly complex surface loading conditions and environments, such as erosion-corrosion and high-stress abrasion, developed within the project provide unique capabilities not previously available. As a result of this project, the static and dynamic design of jaw crushers can also be done more rapidly, utilizing the easy-to-use user interface of the tailored simulation package. The loads obtained due to pitman motion serve as a good starting point for an FEM analysis of the whole machine.

Further information

KEY PUBLICATIONS:

Lindroos, M. 2016. Experimental and numerical studies on the abrasive and impact behavior of wear resistant steels. Doctoral thesis, Tampere University of Technology, Publication 1416, 244 p.

Ojala, N. 2017. Application oriented wear testing of wear resistant steels in mining industry. Doctoral thesis, Tampere University of Technology.

Terva, J. 2017. The effect of compression and sliding movement on the wear resistance of steels and crushing work in mineral crushing. Doctoral thesis, Tampere University of Technology, Publication 1458, 130 p.

Ojala, N., Valtonen, K., Antikainen, A., Kemppainen, A., Minkkinen, J., Oja, O. & Kuokkala, V.-T. 2016. Wear performance of quenched wear resistant steels in abrasive slurry erosion, Wear 354–355:21-31(2016).

Ratia, V., Valtonen, K., Kemppainen, A. & Kuokkala, V.-T. 2016. The Role of Edge-Concentrated Wear in Impact-Abrasion Testing, Tribology Online 11(2):410–416(2016).

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Fine-tuning cast iron properties for optimal performance

Summary of the project's motivation and achievements

The performance of metal components and constructions can be optimized and maximized by using cast-ing technology. Castings can provide versatile material spectra and geometries, and good load-carrying properties for many applications. Constructions can be designed optimally for static and dynamic service, wear, and corrosion.

Transferring casting production to low-cost countries has been a trend in recent years. Finnish foundries are, however, closely linked to their customers and can be an essential asset to them, if the foundries can accustom their production effectively according to their needs. High quality of service and products can be achieved through the production chain only if the first stage – the casting – fulfills these demands. Castings are produced where needed, meaning that the location of their customers' production defines the demand for foundry production. As long as there is production based on cast components in Finland, there will be foundries too. Conversely, the current engineering industry is dependent on availability of domestic castings.

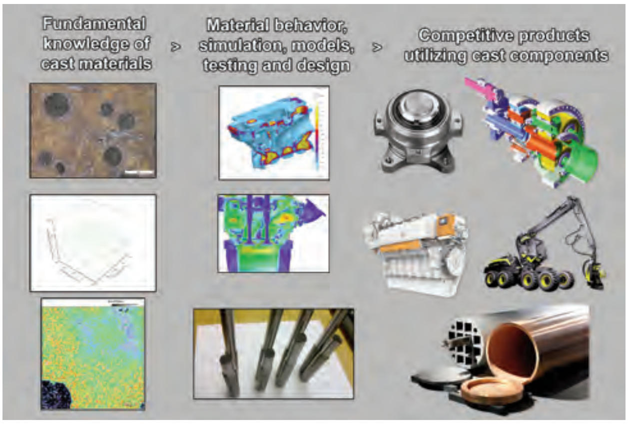

Figure 1. **Impact of research on modern cast products**

There is a growing need to develop better cast irons, especially ductile irons, for demanding applications like wind turbines, diesel engine components, and special machine components. This project targeted enhanced information and knowledge usage for casting users at all levels of the foundry industry, and created new possibilities for casting process research, development, and implementation in order to improve the foundry industry's and its customers' performance and competitiveness.

The main research interest in this project has been the behavior of cast irons in advanced applications and fine-tuning of processes and material properties. Many industrial applications demand specific properties from used materials, ranging from targets like better mechanical properties to optimized thermal transport or long-term stability. The following key results and impacts have been divided into company-specific sections to show how the variable properties available by using cast irons can fulfill very specific demands.

Key results and impacts

COMPONENTA Solution-strengthened ferritic (SSF) ductile irons have shown good mechanical properties in an as-cast state. The key idea in this project for Componenta was to study how austempering heat treatment (ADI cast irons) affects the mechanical properties of these new types of materials. Two standard SSF grades, GJS 500-14 and GJS 600-10, were austempered. Ductile iron grade GJS 500-7 was used as a reference, also in an austempered state. GJS 500-14 gained approximately 30% better yield and tensile strength compared to GJS-500-7, with similar or even better elongation. Austempered GJS-600-10 gained around 20% better yield strength and 25% better tensile strength, but elongation suffered, partly because of some irregular graphite found in the structure. Hardness was 20% higher in both SSF grades compared to GJS-500-7.

Novel SSF-based ADI cast irons provide 30% better yield and tensile strength with similar or even better elongation.

The results show that austempering thin-walled SSF castings without extra alloying is feasible. It is possible to at least double tensile strengths from the as-cast state and still maintain good ductility compared to older ADI cast iron grades. In addition, SSF ductile irons have less alloying additions than standard ferritic-pearlitic ductile irons. However, higher silicon content requires good control of austenizing heat treatment, as the critical temperature is raised higher than in a conventional process. The results gained from this project seems to imply that grade GJS 500-14 could be a very promising choice in austempered form for thin-walled castings, as the lower silicon content, compared to GJS 600-10, makes production easier.

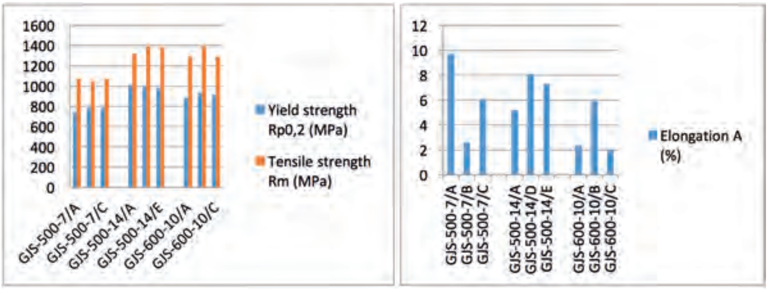

Figure 2. **Key results from austempering tests**

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Company impact

"Participation in material development together with customers is a key factor for success in the manufacturing industry. Participation in the BSA/NOCMA project has brought significant value to our customer co-operation."

Mikko Mykrä, key account manager, Componenta Finland Ltd

Torque density is a main guiding factor in Moventas product development activities. It has been identified to correlate inversely with cost density and to provide concurrently enhanced profitability and lowered cost to customers. Lowered total cost leads to lower levelized cost of energy (LCoE). Approximately 40% of the weight of a wind turbine gearbox comes from toothed steel components, and another 40% from diverse castings. In addition to toothed components, castings play an important role in wind turbine gearboxes as torque-transferring components and housings. This means that there is a substantial weight bound to castings, and certain components are highly loaded.

Castings play a key role in increasing torque density of wind mill gears.

As several technologies are developed simultaneously and the load-carrying capacity of gears and bearings is increased, the bottleneck in increasing torque density is currently the planetary carrier. This component is rather complex in geometry, as it is highly loaded and weighs 3 to 5 tons, depending on the nominal power of the gearbox. The first task was to evaluate the technical and commercial feasibility of different material solutions that could provide enhanced strength compared to the currently used pearlitic grades of ductile irons. According to the reviews, austempered ductile iron (ADI) was seen to provide the best strength gain with a reasonable increase in cost level, which could then be reclaimed in the design process.

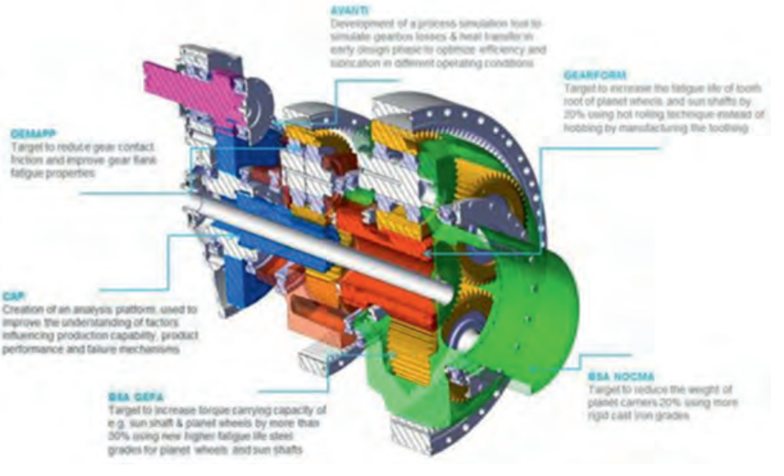

Figure 3. **Development of different key components in various research projects**

Austempered ductile irons are, however, used mainly in smaller components, and rigorous testing must be carried out to secure reliability in wind turbine applications. Current testing procedures required by classification bodies are very time and resource consuming. Thus, an alternative acceptance testing procedure is planned in which casting simulation software is used in test material production, and separate test material can be produced without losing the trustworthiness of evidence compared to destructive testing of actual components.
Initial testing of the austemperability of thick-walled ductile irons is researched and material properties tested. Only after that can the component design process be initiated to optimally benefit from the enhanced mechanical properties achieved by ADI. In testing, it was shown that excellent mechanical properties are achievable even in thick-walled components.

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Even before the BSA NOCMA project, Ponsse was pushing for new approaches and materials in the design of forestry machines. New solution-strengthened ferritic (SSF) cast iron grades have been brought into production, and there is always interest in new usable materials with better engineering properties. Changing over to new materials is not often easy and straight-forward, so the main research objective of Ponsse was to fine-tune production processes with supplying foundries to fulfill the requirements set for SSF cast irons.

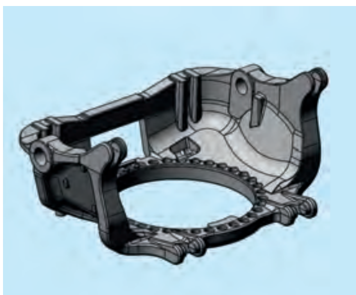

Figure 4. **Many complex cast iron parts are used in the new Scorpion harvester**

Full-scale castings, wide testing, and composition optimization to serve future product designs.

The main focus in NOCMA has been on testing ductile iron grades GJS 500-7 and GJS 600-10. Components cast to earlier parameters showed fluctuations in material properties and microstructures, and did not meet the strict requirements set out for them. Full-scale castings have been studied using destructive testing methods , and chemical compositions have been fine-tuned in cooperation with Componenta. Extensive material data has also been gathered during this project, and can be used in FEM analysis and in the design of future cast components in Ponsse products.

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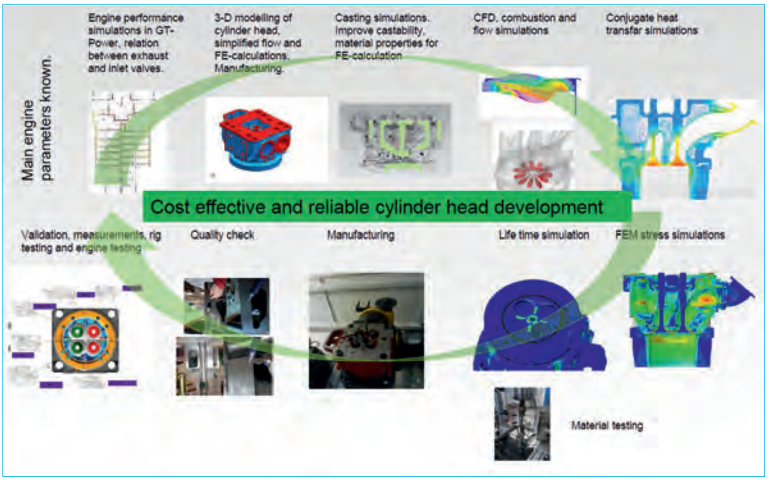
Currently used grades of cast materials are approaching operational limits in highly stressed environments, such as those found in internal combustion engines. More flexible load profiles and higher performance demands call for optimized materials. New tailored materials with better and/or optimized properties are needed to push the limits and solve future design challenges.

Public scientific material data for cast iron types is generally insufficient, and usable data for elevated temperatures is almost non-existent. The project research focused on properties such as thermal conductivity, mechanical strength, and cyclic fatigue behavior of cast irons. This is needed for deeper understanding of the phenomena that cast materials are subjected to at elevated temperatures. Ultimately, the aim is and was to find new materials and/or property combinations that meet higher future demands, in applications like cylinder heads and other thermally stressed applications.

Valuable results gained to be utilized in various simulation tools to evaluate true component behavior in demanding applications.

The results gained from this research area can be utilized in various simulation tools that combine different approaches into true component behavior. Casting simulations for example, generate the distribution of microstructures from component geometry and casting parameters. Thermal and cyclic mechanical property data at elevated temperatures can be combined in a material model, which in turn can be used as a basis for component-level analysis. Advanced analysis approaches are useless if fundamental material knowledge is lacking, and thus the aim of this research is to fill these gaps in current scientific knowledge.



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Company impact

"The results of the BSA/NOCMA project give tremendous help in modern engine design in terms of correct and sufficient material data for new computational tools.

New ductile cast iron grades developed during the project will also have a huge impact on the reliability of our new smart-power plants."

***Aulis Silvonen**, manager, materials and tribology engines, Technology Wärtsilä Finland Oy | Marine Solutions*

The main research objective for Posiva within the NOCMA-project was to study whether solution-strengthened ferritic (SSF) ductile irons could be used as a canister material in the disposal of spent nuclear fuel. Posiva's interest in these materials arose due to their good and promising mechanical properties, among other factors. The main target was to manufacture full-scale iron inserts for the canisters from SSF cast iron, and to do comprehensive studies of the attained properties. Grade GJS-500-14 was chosen for testing.

Full-scale trials with SSF ductile irons as potential canister material for spent nuclear fuel.

Figure 5. **Machined cast iron insert for disposal of spent nuclear fuel**

Two full-scale (1:1) canister inserts of grade GJS-500-14 were cast at the Valmet Technologies foundry, which specializes in thick-walled iron castings in Jyväskylä. Inspections carried out on the first insert revealed a long crack along the insert surface, and the mechanical properties did not fulfill the set requirements. The cause of the crack was investigated, the material microstructure was carefully studied, and based on the evaluations corrective actions were taken during the second casting trial. Based on non-destructive testing (NDT) and early results from tensile testing, the second casting was successful and a testing plan was made to conduct comprehensive mechanical testing for the whole insert. The further testing consists of both non-destructive and destructive testing, and includes radiographic testing, microstructure testing, tensile testing, and fracture toughness testing. A total of 11 test discs were cut along the total insert length, to begin the testing at several testing laboratories using different methods. The preliminary results of tensile testing show that the mechanical properties meet Posiva's requirements. Testing is still ongoing and the results are expected to be finalized during spring 2017.

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The roles of Aalto University and VTT in BSA NOCMA have mainly been in support of company research topics rather than their own separate ones. The main contribution from Aalto has been research on cast iron mechanical and thermal properties at elevated temperatures, in cooperation with Wärtsilä and Componenta, along with austempered ductile iron research, which is also a key part of the research at Moventas and Componenta.

For example, ductile iron elevated temperature thermal conductivities were studied using different chemical compositions from 1 to 4% (Si), while microstructures were also varied by heat treatments. Data was compiled in a regression model;

$$\lambda\left(\frac{W}{mK}\right) = 68.52 + 0.06924x_1 - 19.91x_2 - 0.2125x_3 - 0.00016x_1^2 + 1.997x_2^2 + 0.00347x_1x_2 + 0{,}04551x_2x_3,$$

where x_1 = temperature (°C), x_2 = silicon (%), and x_3 = pearlite (% abs.).

The model was also tested with a few other as-cast cast iron alloys, and it was seen that the proposed model agrees well with measured results.

The main focus of VTT in NOCMA was fracture toughness and microstructural effects .

Research focused on thermal conductivity and fracture toughness gave a solid basis for company-driven projects.

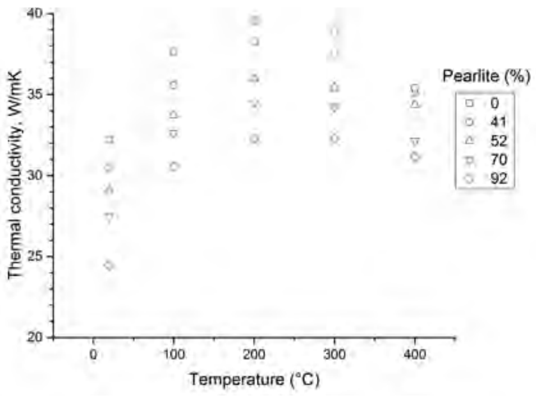

Figure 6. **Temperature dependencies of GJS 500-7 with different microstructures**

Ductile cast irons (DCI) with a fully ferritic matrix have the highest toughness, based on microstructural and fracture toughness studies. Toughness is higher when the content of solid solution-strengthening alloying elements is lower, along with smaller amounts of brittleness-inducing impurities. Of the common elements, especially phosphorus and silicon should be avoided if the main goal is the best toughness. In ferritic DCI, good nodularity, low nodule counts, and small volume fraction of graphite are key in achieving the highest possible upper-shelf fracture toughness. The best lower-shelf fracture is obtained when nodule counts are high. A low DBTT results when the nodule count is high.

An increase in pearlite fraction, phosphorus, and silicon decreases toughness values and raises the transition temperature remarkably. Fully pearlitic cast irons have the lowest level of toughness. In pearlitic-ferritic iron ferrite, ferrite around the graphite nodules increases fracture resistance effectively due to yielding of ductile ferrite.

Tempered martensitic matrices give better combinations of strength and fracture toughness than pearlitic matrices. Austempered versions (ADI) have the highest toughness at specified hardness and strength level.

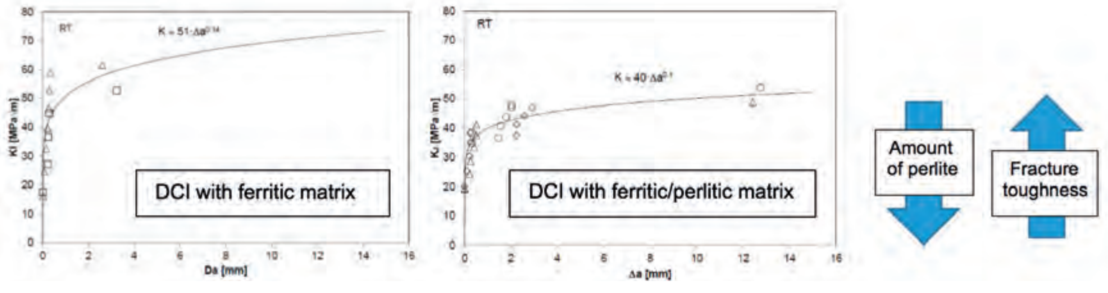

Figure 7. **Effect of microstructure on fracture toughness of ductile iron**

When the target is to have the highest toughness in industrial ferritic castings, in which there are commonly traces of pearlite, ferritizing heat treatment is suggested. Compared to conventional DCIs, silicon-alloyed irons retain greater strength because of the high solid solution effect in ferrite by silicon.

If the need is to have high strength, pearlitizing heat treatment can be performed. In this case, toughness will be sacrificed. A compromise to provide both greater toughness and strength is to spheroidize pearlite cementite. In spheroidizing, annealing times and temperatures are most critical, as cementite is prone to disappear totally by quick diffusion of carbon into graphite nodules, resulting in a fully ferritic matrix. The most advantageous matrix microstructure might be one with a ferrite shell around graphite nodules and spheroidized pearlite (partially or completely spheroidized cementite lamellae) in nodule-free areas.

Further information

MASTER'S THESES:

Jalava, K., Alternative cylinder head materials.

Karhula, L., Austemperability of solid solution-strengthened ferritic ductile irons.

Okunnu, R., High strength solution-strengthened ferritic ductile cast iron.

Partanen, O., Optimization of solid solution-strengthened ferritic ductile iron production by thermal analysis and solidification simulation.

Puustinen, E., Enhancing mechanical properties of solid solution-strengthened ferritic spheroidal graphite cast iron with austempering heat treatment.

FUTURE PUBLICATIONS (2017):

Jalava, K., Soivio, K., Laine, J. and Orkas, J., Effect of silicon and microstructure on spheroidal graphite cast iron thermal conductivity at elevated temperatures, Journal of Materials Engineering & Performance, submitted.

Jalava, K., Soivio, K., Laine, J. and Orkas, J., Comparison of elevated temperature thermal conductivity of some gray, compacted graphite and nodular cast irons in as-cast and austempered conditions, to be submitted in 2017.

Jalava, K., Okunnu, R., Soivio, K., and Orkas, J., Influence of Cobalt addition on mechanical behaviour of solution strengthened ferritic ductile Iron, to be submitted in 2017.

Jalava, K., Vaara, J., Laine, J. and Orkas, J., Effect of ferrite and pearlite on spheroidal graphite cast iron Dynamic Strain Aging at elevated temperatures, to be submitted in 2017.

Karjalainen-Roikonen, P., Virta, J., Kokkonen P., Fracture toughness and microstructure of GJS with different heat treatments, to be submitted in 2017.

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Novel super high strength steels boost sustainability and high performance

Summary of the project's motivation and achievements

Steels provide both environmentally and economically the best material solutions for a wide range of applications. In recent decades, scientific advances in our understanding of strength and formability have enabled the development of thin, lightweight, high-strength, high-performance steel sheets for the automotive industry. However, there is a need for similar advances in our understanding of the essential properties of thicker steel products to enable weight savings and the more efficient use of energy and resources in a much wider range of applications, like machinery, vehicles, ships, and offshore structures.

The ambitious goal of the project "Novel Super-High-Strength Steels, Super HSS" is to develop structural steels with yield stresses up to 1500 MPa and novel abrasion-resistant steels in the range of 400–700 HBW, without the excessive use of expensive alloying elements to ensure usability. This makes it possible to reduce the weight of structures, creating opportunities for major global environmental impact by reducing the use of valuable raw materials and energy, as well as reducing CO_2 emissions.

The technical solution for this is an advanced hot-rolling technology called "direct quenching," which was developed at SSAB (at that time Rautaruukki Oyj) in 2002. The innovation won the 2012 Finnish Engineering Award and has brought Finland to the forefront of global hot-rolled steel development. However, the metallurgy of direct quenching was still in its infancy: to enable an attractive product portfolio to be built, new scientific knowledge was developed regarding the factors controlling properties such as toughness, bendability, and hydrogen-assisted cracking. The project includes a five-item work package, of which four items will focus on steel concepts and one on a weldability toolkit.

Work package of the project Super HSS (situation at the end of the BSA program):

1) Super-high hardness (550–700 HBW) steels for extreme wear resistance
   - 550 HBW is being commercialized and 600 HBW is in the laboratory research phase.
   - Development projects on 650 and 700 HBW steels were planned to start in Q4/2017.
2) Super-high-strength (960–1500 MPa) strip steel with supreme formability and weldability
   - Novel StrenxTM 900–960 steels are being commercialized and S1100 is in the laboratory research phase.
   - The development process for steels 1300 and 1500 was planned to start in Q1/2018.
3) Super-high-strength (960–1300MPa) heat-treated steels for demanding structural applications
   - New S900/960 type steels are in the laboratory research phase.
   - The development process for steels 1100 and 1300 was planned to start in Q4/2017.
4) Novel direct-quenched steel concepts for (super) bainitic steels
   - A lot of laboratory work and fundamental research has been done (note: the idea was patented in 2014). The next step would be comprehensive analysis of full-scale trials and planning of the next phase.
5) Weldability of ultra-high-strength steels
   - A preliminary welding model for the S700 type of steels was made. The next step would be to extend the model to 900–1100 MPa steels and commercialize it to members of the consortium.

Because the government of Finland terminated the funding of the BSA program, less than half of the planned R&D work was realized and only 20% of the commercial targets can be achieved.

This development process has achieved many ideas and possibilities for novel ultra-high-strength structural, abrasion-resistant steels and steel-based products that outperform their rivals. These advances have not gone unnoticed, and competing companies abroad are also trying to follow the Finnish example. Therefore, it is really important that Finland is able to further develop the application of this technology and thereby

Direct quench technology opens new possibilities.

maintain its leading position. Despite their excellent properties, the products developed so far can achieve even better combinations of properties, like formability and toughness, which will make them even more competitive and usable in a wider range of applications with bigger markets. In addition, there are numerous possibilities to use the direct quenching technology platform to make products requiring lower strengths than those produced so far. In this case, direct quenching will make the products more sustainable by reducing the need for expensive alloying elements. They will also be easier to weld and shape, and will be safer and longer lasting due to their toughness and fatigue strength.

NEXT-GENERATION ULTRA-HIGH-STRENGTH STEEL FAMILY

SSAB is a market leader in the production of ultra-high-strength steels. Therefore, the main focus was not only to develop new steel grades but also to improve the mechanical properties and usability of direct-quenched and direct-quenched tempered steels using new combinations of chemical composition and microstructure. Significant attention has also been paid to cleanliness in steel-making and grain-size control during the thermomechanical process.

Mechanical properties of direct-quenched ultra-high-strength steels

The effect of austenite pancaking in the non-recrystallization regime on microstructure and mechanical properties, especially bendability, was investigated in direct-quenched ultra-high-strength strip steels with martensitic-bainitic microstructures.

Lowering the finishing rolling temperature (FRT) increased the total reduction in the non-recrystallization region (Rtot). Niobium microalloying increased Rtot while variations in C, Mn, and Mo did not affect Rtot to the same extent as Nb. A decrease in the FRT increased the incidence of softer microstructures such as ferrite and granular bainite in the sub-surface layers. The microstructures at the centerline comprised auto-tempered martensite with some bainite.

Bendability is poorer with the bend axis perpendicular rather than parallel to the rolling direction (RD) and is further impaired with increasing hardness below the sheet surface. An intense ~{112}<111>α shear texture combined with upper bainite containing MA islands in the sub-surface region is shown to be detrimental to bendability when the bend axis is perpendicular to the RD. This anisotropy of bendability can be explained by the appearance of geometric softening in grain clusters belonging to this texture component when the bend axis is perpendicular to the RD. Shear localization is prevented, however, by the presence of a sufficiently thick subsurface microstructure with an adequate work hardening capacity, namely ferrite + granular bainite rather than ferrite + upper bainite. The strain required to initiate strain localization can be increased and good bendability thereby achieved, even in the presence of detrimental texture components, by ensuring the presence of a sufficiently soft subsurface layer extending to a depth of approximately 5% of the total sheet thickness.

The above beneficial microstructures can be obtained and good bendability ensured in direct-quenched strip steel with a yield stress of above 900 MPa, together with good impact toughness, provided a suitable combination of chemical composition and processing parameters is selected and sufficient attention is paid to steelmaking operations to obtain a proper inclusion structure (Figure 1).

Company impact

> "The new hot-rolling ideas are in test use at the SSAB Raahe steel mill and the first results are promising."
>
> ***Pasi Suikkanen**, product development director, SSAB Europe Oy*

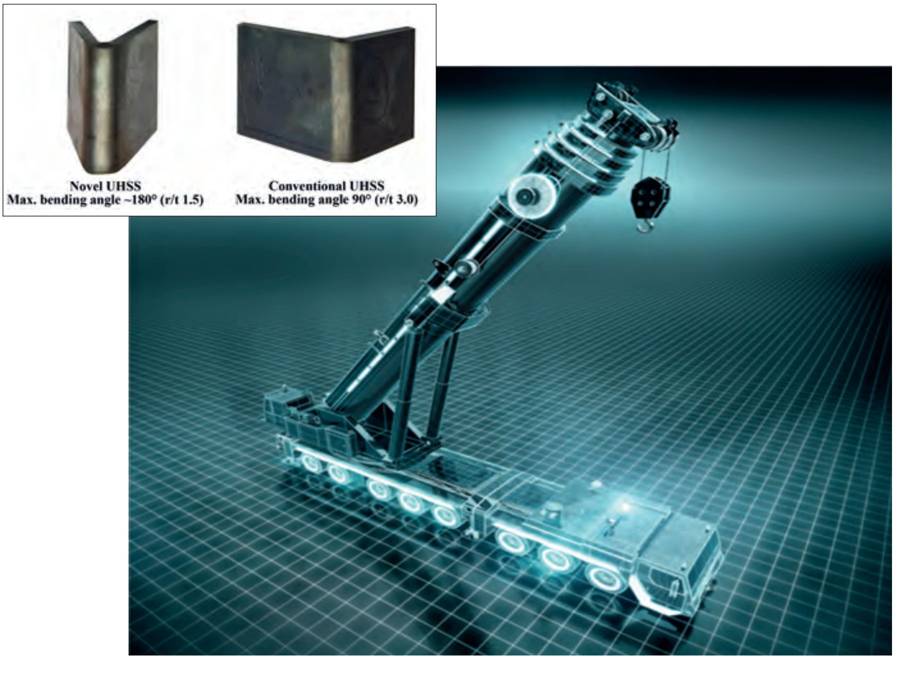


Figure 1. **Superior bendability of novel StrenxTM 900/960 MC and a typical application. StrenxTM 900–1100MC enables lightweight design, for instance, in transportation and lifting/handling segments**

Mechanical properties of tempered direct-quenched ultra-high-strength steels

In the novel super-high-strength (960-1300MPa) heat-treated steel concept, conventional tempering of direct-quenched cut sheets was replaced with single, long bell-furnace tempering, which creates a unique and efficient coil tempering process. In laboratory-scale experiments, modern tempering-resistant compositions were developed, which will be introduced later at an industrial level. The novel composition combined with an optimized thermo-mechanical treatment and tempering process produces a unique microstructure, including tempered martensite and a small amount of ferrite. This microstructure provides a high strength of DQ steel with superior bendability and toughness (Figure 2).

The unique microstructure provides superior mechanical properties for novel super-high-strength steels.

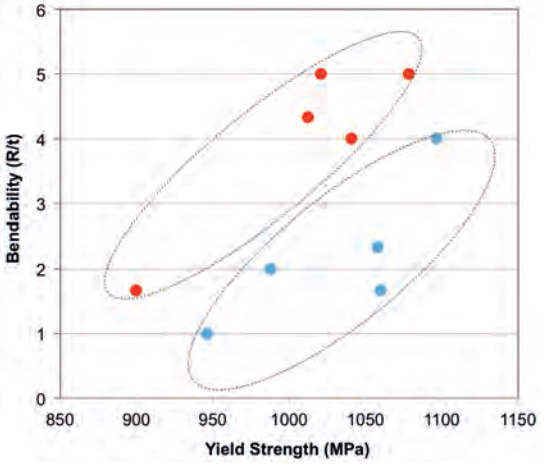


Figure 2. **Yield strength – Bendability correlation of developed DQ (blue circle) and DQ-T (red square) steels. A smaller R/t-value (bending radius/plate thickness) means better bendability**

Toughness fundamentals for ultra-high-strength steels

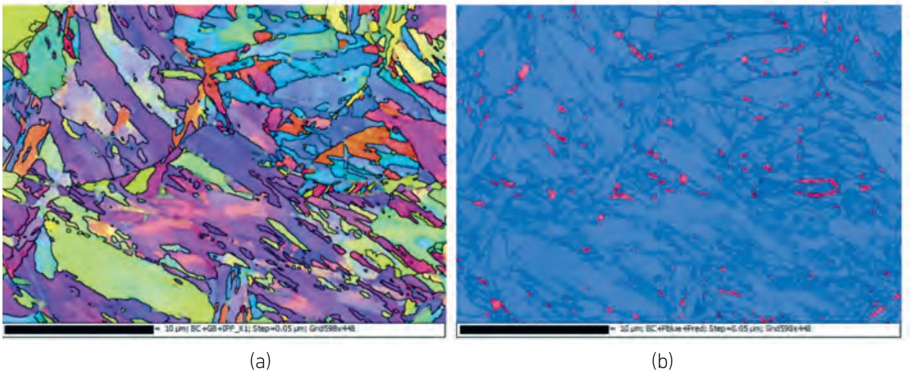
The main target is to improve the fracture toughness of ultra-high-strength structural steel and to understand the relationship between the transition temperature, the fracture toughness reference temperature T0, and the impact toughness transition temperature T28J. The ambition was to establish the microstructural factors that control toughness transition temperatures in ultra-high-strength steels.

The results considering the transition temperatures enable reliable estimation of the fracture toughness reference temperature T0 and hardened weld metals both on a material property level and in an engineering tool that has potential for implementation in future standards and design rules. Findings on low-temperature hydrogen embrittlement emphasize the importance of low hydrogen content in high-quality steelmaking, and the previously controversial matter that hydrogen content cannot be neglected in the question of ductile-brittle transition temperature region properties. Collaboration has been done with VTT (Finland) and NTNU (Norway). The targets were mostly achieved.

Direct-quenched and partitioned steels

The main target of this project was to evaluate the outcome of the processing route adopted for the development of industrially rolled and direct-quenched and partitioned (DQ&P) strips steels. The targets in respect of yield strength and ductility have been achieved, but there is scope for further improvement in respect of higher tensile strength, elongation, and enhanced strain-hardening capability by adapting to a lower quenching and partitioning temperature.

FESEM-EBSD and TEM measurements clearly revealed the extent of tempering and the presence of a low substructure. Retained austenite was often not like interlath films, but more like coarse pools or grains somewhat elongated along the laths (Figure 3).



(a) (b)

Figure 3. FESEM-EBSD measurements of 0.2C-2Mn-1.5Si-0.5Cr type DQ&P steel

The project leader of SSAB Corporate, Saara Mehtonen, comments: "The results shows that the DQ&P route will be a new possibility for developing martensitic or nanostructured bainitic steels with ultra-high strength and toughness." Therefore, it is annoying that the implementation process of this patented innovation cannot continue.

Weldability of ultra-high-strength steels

The welding tests of StrenxTM 700 show that welding decreases the mechanical properties of TMCP steels less than the mechanical properties of Q&T steel. The most notable differences occurred in the Charpy-V tests, when the notch was located at fusion line+1 mm and at fusion line+3 mm (Figure 4, on the left). Considering the tensile test results (Figure 4, in the middle), welding and increasing heat input decreased the elongation and yield strength of Q&T more significantly than the elongation of TMCP steels. On the other hand, Q&T steel maintained tensile strength better than TMCP steels. The decrease of the strength was caused by the localization of the strain at the softened region in the HAZ, reaching a peak temperature of about 950°C, as indicated by Sysweld-based modeling. Figure 4 (on the right) shows the strain localizations measured by digital image correlation (DIC).

In a weldability analysis of StrenxTM 960, a model between prior austenite grain size and hardness for CGHAZ was developed and is ready for further exploitation. In this model, a Hall–Petch-type relationship between prior austenite grain size in CGHAZ and hardness was evaluated. Among the conclusions, the main emphasis should be given to the fact that ICCGHAZ, with low heat input, presented a significant improvement in relation to CGHAZ.

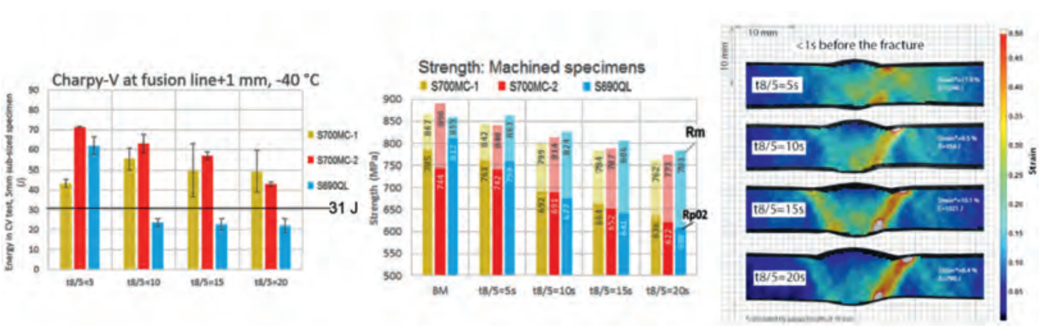


Figure 4. Welding tests: Notable differences between the materials considering Charpy-V (left) and tensile tests (center) results. The localization of the strain and the effect of increasing heat input are presented on the right

NEXT-GENERATION ABRASION-RESISTANT STEEL FAMILY

The project has shown that Hardox, Raex and Ramor can be produced effectively in Raahe.

Abrasion-resistant steels are clearly niche products but widely used in many applications where the wear is the design criterion. Raex and especially Hardox are the most famous brand names in high-strength, wear-resistant steel families with favorable hardness and good impact toughness. These steels can be used in mining machines, wearing parts for concrete mixing plants, wood-processing machines, platform structures, feeders, funnels, and so on. They can also enable innovative design and lightweight products, improving energy efficiency and thus saving costs. The concept of Raex was developed in an earlier program, FIMECC DEMAPP (2009–2014), and in the technology program NewPro (2004–2009). This project is focusing on end-users' needs (i.e. developing novel steel applications), finding new ideas, and fine-tuning the products (Figure 5).

a) (b)

Figure 5. (a) Welded excavator bucket made of new Raex 400 and 500; and (b) New "Hardox 450 strip in my tipper body"

The cost-effective abrasive-resistant steel solutions of SSAB are based on using direct-quenching technology to produce low-alloy martensitic steels with a hardness range of 400–500 HBW. Traditionally, these steels have been produced by reheating a hot-rolled plate and then water-quenching it to a martensite state. In the case of Raahe, the water for quenching is applied immediately after thermomechanical hot rolling. *"This saves capital investment, speeds up production, saves energy, and reduces costs", concludes product development manager Pertti Mikkonen at SSAB Europe Oy*. It also improves the surface quality and dimensional accuracy of the abrasion-resistant and protection plates.

Protection steels also have high hardness and strength, but in addition, they have tested ballistic or blast- resistant properties, as required for security vans and military vehicles (Figure 6).

Figure 6. Personnel carrier with critical parts made of new Ramor 550 and new Ramor 450

Further information

KEY PUBLICATIONS:

Wallin, K., Pallaspuro, S., Valkonen, I., Karjalainen-Roikonen, P. & Suikkanen, P. 2015. Fracture properties of high performance steels and their welds. Engineering Fracture Mechanics 135, 219–231.

Somani, M., Hannula, J., Kaijalainen, A., Misra, D. & Porter, D. 2017. An Appraisal of Direct Quenching for the Development and Processing of Novel Super-High Strength Steels. Materials Science Forum 879, 1819–1827.

Kaijalainen, A.J., Suikkanen, P.P., Karjalainen, L.P. & Porter, D.A. 2016. Influence of Subsurface Microstructure on the Bendability of an Ultrahigh-Strength Strip Steel. Materials Science and Engineering A 654, 151–160.

Kaijalainen, A.J., Liimatainen, M., Kesti; V., Heikkala, J., Liimatainen, T. & Porter, D.A. 2016. Influence of Composition and Hot-Rolling on the Subsurface Microstructure and Bendability of Ultrahigh-Strength Strip. Metallurgical and Materials Transaction A 47, 4175–4188.

Saastamoinen, A., Kaijalainen, A. & Porter, D. 2016. Effect of titanium and nitrogen content on the microstructure, hardenability and mechanical properties of direct quenched and tempered ultra-high strength structural steel. 5th International Conference on Thermomechanical Processing. Associazione Italiana di Metallurgia, 5050.

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NOVEL STEEL CONCEPTS

P3
SP3

Leeni Aula/Outokumpu Stainless Oy
Pekka Nevasmaa/VTT Technical Research Centre of Finland Ltd
Suvi Papula/Aalto University
Jukka Kömi/University of Oulu

From concepts toward new applications

Aim of the project

Stainless steels are a broad family of highly corrosion-resistant iron-chromium alloys that can be characterized to be life-cycle efficient, durable, and sustainable materials for many engineering applications. Despite having a history of more than 100 years, there is still vast potential to improve the life-cycle performance of stainless steels. The ambition of this subproject was to build scientific and technological knowledge to develop novel, cost-efficient structural stainless steel concepts exhibiting an excellent combination of strength and toughness and also to remove barriers to the effective utilization of novel sustainable stainless steels in current and new application areas.

The aim of the new steel development subtask was to explore possibilities to utilize new multiphase microstructural concepts that would surpass the typical ferritic structural stainless steel grade EN 1.4003 in corrosion resistance without sacrificing lean alloying cost and key mechanical properties, especially toughness. From the early stages of the project, it was evident that improvement in corrosion resistance would require higher alloying cost. In addition, it was known that an increase in chromium content would also increase the brittleness of the ferritic microstructure and consequently degrade low temperature toughness. Consequently, it was important to focus research work on multiphase steels. The main achievements from the research work were the development of two novel steel groups with martensitic-austenitic and ferritic-austenitic microstructures. However, due to termination of funding, the implementation of basic research knowledge beyond laboratory scale was not possible.

The aim of removing barriers to the effective utilization of novel sustainable stainless steels was to open markets to novel 21% Cr stainless steel grades by improving their properties and usability. International standardization work was carried out to introduce new stainless steels Core 4622 (EN 1.4622) and Supra 316plus (EN 1.4420) for a new revision of the pressure vessel standard EN 10028-7 and also of many ASTM standards. **The main achievements from this work were approval of both of these grades to EN 10028-7, and Supra 316plus to ASTM A240/A240M, A312, A249, A269, A358 and A554.** In addition, work on implementing steels in other standards is in progress.

New grades approved to EN 10028-7, and Supra 316plus to ASTM standards.

Key results and impacts

Novel structural stainless steels

Nearly 30 experimental laboratory steels were processed in a small-scale pilot plant. The chemistry of these multiphase steels was divided into two main groups: low chromium, low carbon martensitic-austenitic steels and high chromium, high nitrogen ferritic-austenitic steels.

The mechanical properties of novel martensitic-austenitic steel clearly surpassed those of reference steel EN 1.4003.

The main results showed that exceptional toughness and high strength properties could be obtained in steels with a martensitic-austenitic microstructure and that performance clearly surpassed reference steel EN 1.4003. Estimated T_{28J} transition temperatures were often below -100°C with yield strengths of 500–900 MPa. Ferritic-austenitic steels were more susceptible to low-temperature brittleness, especially those steels that had coarse ferrite grains and a phase balance more toward ferrite than austenite. Inclusions had no marked effects on examined properties.

Cost-efficient Mn-rich alloying in martensitic-austenitic steels, as opposed to conventional Ni-rich alloying, did not drastically alter mechanical properties. In fact, the Mn-rich alloying accompanied with a well-engineered tempering process optimized the amount, composition, and structure of reverted austenite, which was seen to be very beneficial in improving ductility via a transformation-induced plasticity (TRIP) effect. The compositional range and method of manufacturing steel with significantly improved tensile ductility were developed and a patent application was filed. In addition, Mn-rich alloying also produced a wider processing window, making industrial applicability more favorable.

Improvements in tensile ductility due to the TRIP effect were also seen in ferritic-austenitic steels due to controlled low stability of the austenite phase. Martensitic transformation occurred during plastic deformation and it significantly increased the work hardening of the material. As a result, the ultimate tensile strength and elongation were markedly higher in these steels in comparison to typical duplex stainless steels, and that higher amount of ferrite

Modeling revealed large local austenite areas to be more detrimental to simulated elongation than large ferrite grain size.

(up to 70%) was not detrimental to elongation. The first modeling round results revealed large local austenite areas to be more detrimental to simulated elongation than large ferrite grain size. Fine grain size and lamellar spacing of the phases is preferred, resulting in the best mechanical properties. A method of preparing samples for microstructural characterization was improved that prevented martensitic transformation in sample preparation (Figure 1).

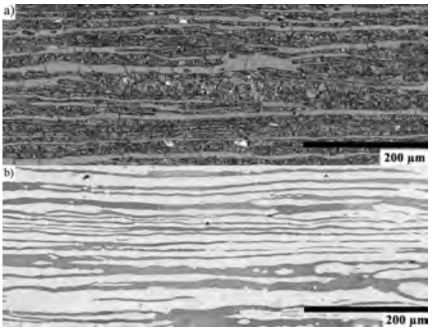

Figure 1. **Microstructure observed in the same steel after a) mechanical polishing (ferrite+martensite) and b) electropolishing (ferrite+austenite)**

Hydrogen-induced delayed cracking was generally not a problem in the examined steels. The amount of hydrogen found in ferritic-austenitic stainless steels varied between 1.5–3.5 ppm (by mass-%), which is somewhat lower than the typical level in austenitic stainless steels. However, ferrite can be embrittled with very low levels of hydrogen present, and the presence of martensite increases the hydrogen-induced cracking susceptibility. In the steels with metastable austenite, in highly plastically deformed areas along the crack path, austenite was transformed to martensite (Figure 2a), deteriorating the crack arrest tendency of the austenite in a ferritic-austenitic microstructure. The fracture mode was predominantly cleavage in the ferrite and somewhat more ductile quasi-cleavage in the austenite phase (Figure 2b).

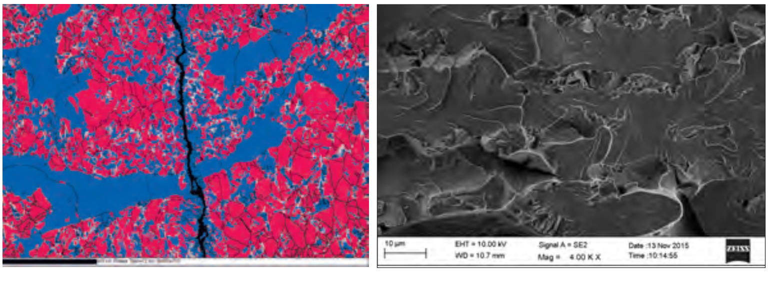

Figure 2. **a) Crack path in a ferritic (blue)–austenitic (red) microstructure, showing localized transformation to BCC-martensite and b) fracture surface illustrating different fracture modes of the phases**

Excessive Mn alloying reduced the corrosion resistance gradually in martensitic-austenitic steels. Most importantly, a modified pitting corrosion-resistance formula containing Mn as a negative term was seen to be very accurate to represent the performance of laboratory steels. It was also seen in ferritic-austenitic steels that corrosion performance was very dependent on annealing temperatures and ferrite content, so that higher annealing temperatures and ferrite contents were generally detrimental.

Removing barriers to utilization of novel stainless steels

Outokumpu has previously developed and patented two novel, high chromium stainless steel grades, Supra 316plus and Core 4622.

Outokumpu Supra 316plus (EN 1.4420, ASTM UNS S31655) is a novel, lean austenitic stainless steel grade that is a competitive alternative to well-known austenitic acid proof grades EN 1.4401 and EN 1.4404. The price of the grade is less volatile, as it contains less nickel and molybdenum than comparable steels EN 1.4401 and EN 1.4404. Higher chromium and nitrogen contents with moderate molybdenum and nickel improve corrosion resistance compared to austenitic EN 1.4401 and EN 1.4404. It has higher strength due to nitrogen alloying, and it is easy to form and weld. The grade is ideal for use in a variety of applications, including tanks, tubes, heat exchangers, and water treatment, as well as in architectural indoor and outdoor applications. Figure 3 shows an example of a wine tank application.

Figure 3. **Outokumpu Supra 316plus is being tested in wine tanks by a leading European manufacturer. "It has better resistance to corrosion, compared to the standard EN 1.4401 grade, and more strength," indicates the customer**

Outokumpu Core 4622 (EN 1.4622, ASTM S44330) is a novel ferritic stainless steel grade that is a competitive alternative to well-known austenitic basic grades EN 1.4307 and EN 1.4301. The price of the grade is less volatile, as it is Ni-free. It is also a more corrosion-resistant option for commonly used ferritic steel grade EN 1.4509. Core 4622 has been tested for various deep-drawing applications (see Figure 4 for an example). The greatest customer benefit in these applications comes from the fact that the grade is virtually roping free; final products do not require as much polishing compared to other ferritic stainless steel grades, which saves time and money in our customers' processes.

Figure 4. An Italian household goods manufacturer has been testing Core 4622: "To test this raw material, we made a deep drawing pot. The result was impressive. The test proves that Core 4622 performs no less than austenitic stainless steel such as 1.4301, our current standard. Furthermore, Core 4622 is virtually roping-free," comments a company representative

Product properties of Supra316 plus and Core 4622 were studied in order to get them to the European and American standards that regulate stainless steel usage for different applications, thus enabling wider utilization of those steels. Both grades were accepted to the standard "Flat products made of steels for pressure purposes – Part 7: Stainless steels." In addition, Supra 316plus was accepted to several ASTM standards.

Company impact

"Stainless steel was discovered 100 years ago in today's Outokumpu. However, the world needs modern stainless steels that meet the requirements of a changing business environment. Standardization has a key role in our business development, to which the BSA project has provided valuable information."

Juha Kela, product manager, Outokumpu

Mechanical properties were studied both for cryogenic temperature applications and high temperature applications. Supra 316plus had interestingly different fire-resistance design properties from normal austenitic stainless steels. Formability data for simulations for grades Supra 316plus and Core 4622 was studied in collaboration with Lapland University of Applied Sciences, and grain growth was also studied in order to optimize product properties.

Ferritic stainless steels are often considered to be less resistant against localized corrosion, especially crevice corrosion, than austenitic stainless steels, and therefore the crevice corrosion resistance of Core 4622 was studied closely in cooperation with the BSA P1.1 Green Processes (GPRO) project. **Core 4622 was observed to have improved crevice corrosion resistance compared to ferritic grades containing lower amounts of chromium, enabling its usage in a wider range of applications.**

Core 4622 was observed to have improved crevice corrosion resistance.

For a deeper understanding of the structural low-temperature fracture behavior of ferritic stainless steels, two advanced grades, Moda 4003 (EN 1.4003) and Core 4622, were studied using small-scale fracture mechanics and Charpy impact testing, as well as verification loading tests applying large-scale U-profile beams. In this way, the effect of welding residual stress on the propensity to brittle fracture was analyzed, and temperature ranges for overall ductile behavior, as well as for cleavage fracture dominated brittle failure, were determined.

Toward cryogenic temperature use

Low temperature tensile testing facilities were specifically established and applied. Research has shown that the investigated austenitic stainless steel, EN Supra 316plus, has an excellent combination of strength and ductility at the tested temperatures –80°C, –150°C, and -196°C. (Figure 5). Compared to EN 1.4044, Supra 316plus exhibited clearly higher yield strength (Rp0.2) and equivalent or slightly greater elongation (A50), with the difference increasing toward lower temperatures in particular. Thus, the combination of very low temperature strength and ductility for Supra 316plus proved far better than in the case of EN 1.4044. The verified test results were used for the European EN 10028-7 standardization process. **As a result, the application area of austenitic steels was widened to, and guaranteed for, cryogenic temperature applications, such as liquefied natural gas (LNG), by introducing the new Supra 316plus for new revision of the pressure vessel standard EN 10028-7, Table E.**

The application area of austenitic steels was widened to cryogenic temperature applications. This opens new applications such as LNG storage and transportation.

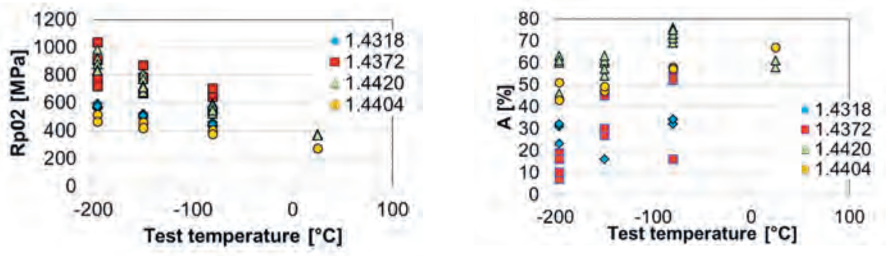

Figure 5. **Austenitic stainless steel, Supra 316plus, has an excellent combination of strength (left) and ductility (right) at cryogenic temperatures**

Understanding structural fracture behavior

With respect to the two novel ferritic stainless steels, the intention was to gain a realistic description of the actual fracture characteristics in thin-section structures at sub-zero temperatures with associated specimen constraint and inherent fracture micromechanisms as a function of temperature. According to the standard small-scale fracture mechanics tests, Moda 4003 appeared well suited to low-temperature applications, whereas the higher Cr grades suffered from inferior toughness at sub-zero temperatures. It is known, however, that standard fracture mechanics tests tend to be clearly conservative in relation to the actual large-scale structural behavior of thin sections (mainly due to different constraints) (Figure 6).

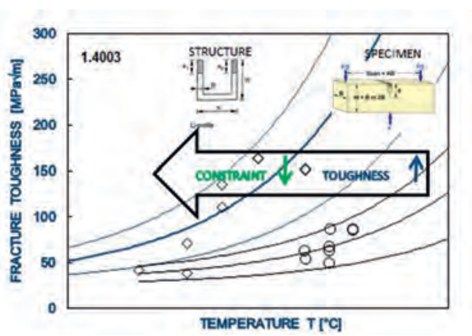

Figure 6. **For thin-walled structures made of ferritic stainless steel, constraint is lower, resulting in higher fracture toughness and a lower transition temperature compared to a small, standard fracture mechanical specimen**

Applying the U-profile beam 3-point bending experiments enabled a demonstration of fracture behavior being more representative of actual thin-section structural parts. This was accomplished via the incorporation of several relevant structural features into one specimen configuration, such as: (i) allowance of a large amount of crack growth, resulting in realistic failure modes; (ii) stress distribution consisting of combined bending and tension at the crack tip; (iii) inclusion of the influence of welding residual stresses; and (iv) constraints being representative of thin-section structural members. As a result, the effect of welding residual stress on the propensity to brittle fracture was found nearly insignificant, obviously due to the small-section thickness and only modest strength. This translates to a somewhat safer application of welded FSS structures than anticipated previously. The fracture load–temperature data from the U-profile beam tests showed that the ductile-to-brittle transition region for Moda 4003 situates at temperatures as low as –100°C or below, which is approximately 80°C lower than for Core 4622. Despite this, and unlike the standard fracture mechanics tests, the large-scale U-beam tests also imply that Core 4622 might be safely used in thin-section structural parts operating at modest sub-zero temperatures around –20°C, which is an encouraging finding that is yet to be confirmed by ongoing detailed fracture-mechanics analyses of the experimental data. Whatever the case, the main outcome here is an indisputable extension of the application range of the new in relation to conventional ferritic stainless grades.

Further information

KEY PUBLICATIONS:

Miettunen I., Anttila S., Kaupinmäki T., Porter D. 2016, The effect on Ni, Mn and tempering on austenite reversion in 13% Cr martensitic stainless steel, 5th International Conference on Thermomechanical Processing 2016, 26–28 October, 2016, Milan, Italy.

Papula, S., Anttila, S., Sarikka, T., Talonen, J., Virkkunen, I., Hänninen, H. 2016, Strain hardening of cold-rolled lean-alloyed metastable ferritic-austenitic stainless steels, Materials Science and Engineering A, 677 11–19.

Juuti T., Uusikallio S., Kaijalainen A., Heinonen E-, Tun Tun N. and Porter D. 2016, The effect of sample preparation on the microstructure of austenitic-ferritic stainless steel, Materials Science Forum 879, 873–878.

Anttila, S., Lauhikari, V., Heikkinen, H-P. Porter, D. 2016, Slag island characteristics and weld penetration in very low sulphur 18% Cr stabilized ferritic stainless steel. Welding in the World 60, 485–496.

Nevasmaa, P. & Karjalainen-Roikonen, P. 2016, Low-temperature fracture characteristics of new 11% Cr and 18–21% Cr ferritic stainless steel grades for welded structures. IIW-Doc. IX-2562-16. Proc. Conf. "69th IIW Annual Assembly and International Conference", Melbourne, 10–15 July 2016. Australia: The International Institute of Welding (IIW), 22.

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Digitalizing materials development

Background

The BSA program includes three industrially focused R&D projects related to the development of new steel 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. The **Modeling tools and optimal material design** (MTOM) sub-project is a novel instrument that aims 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 generic knowledge of materials and their development was used in the R&D work of projects P1-3 in the BSA program. MTOM is a competence project that supports doctoral projects and the implementation of the results in industrial problems. The main purpose of MTOM 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 PhD theses related to the DIMECC Breakthrough Materials Doctoral School. The purpose of the modeling part was to identify the state-of-the-art means and methods for multiscale materials modeling, to make these methods available to the DIMECC Breakthrough Materials Doctoral School and the BSA program, and to develop new methods beyond the current international state-of-the-art in close co-operation with the Doctoral School PhD projects and other SPR and IAR projects of the BSA.

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

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 wide variety of techniques and methods were used by the participating organizations for the characterization of constituent properties from macro to micro and nanoscale. Industry also needs improved design rules to fully exploit the properties of novel advanced steels. 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.

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

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. The results obtained in this project are internationally ground-breaking and were only made possible by a wide collaboration between both Finnish and particularly international partners and networks.

Objectives

The goal of MTOM was to derive a modeling concept and package for the PhD projects of the DIMECC Breakthrough Materials Doctoral School and for the projects of the BSA and HYBRIDS programs, and to ensure and aid in the effective implementation of modeling-related tasks. The results will be compiled in a platform of multiscale modeling tools that can be applied to the solution of specific modeling problems. The MTOM subproject oversees the implementation of the modeling activities within the Doctoral School and integrates both directly and via PhD projects with the modeling work carried out in BSA and HYB program 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 about 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 based on them
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.

The particular subject areas identified for MTOM in the BSA program on the basis of the PhD projects were the following:

i) Fracture mechanics-based multiscale modeling and assessment of high-strength and stainless steels and welds

ii) Multiscale modeling and optimization of wear- and corrosion-resistant steels and composites

iii) Modeling and optimization of deformability, bendability, and formability of high-strength and stainless steels

Key results and impacts The major part of the work carried out in MTOM aimed to assist other projects. Therefore, most of the results are reported in detail in the reports concerning each individual sub-project. Because of this, only highlights of selected key results and their impacts are summarized in the following, focusing on results that are likely not reported elsewhere.

T1 Methodology and compilation

New methods were developed to generate microstructures directly from Electron Back-Scattered Diffraction (EBSD) data. Similarly, compilation methodologies were developed for generating microstructures of rocks for crushing simulations. These methods were essential for the development of microplasticity-based models for steels to evaluate their failure, fracture, and wear behavior in various use cases. Rock modeling was further used for the dynamic simulation of the jaw crushers, which combined the microstructural features of the steel and the fracture and fragmentation behavior of the rock itself. The crystal plasticity approaches were extended to duplex microstructures, to study the dependency of lean duplex steel toughness on individual phase morphology, fraction, and distribution (see Figure 2 below).

Microscopy data was used to create microstructure models of complex multimaterial systems, such as rock crushers.

Figure 1. Microstructures generated from EBSD data

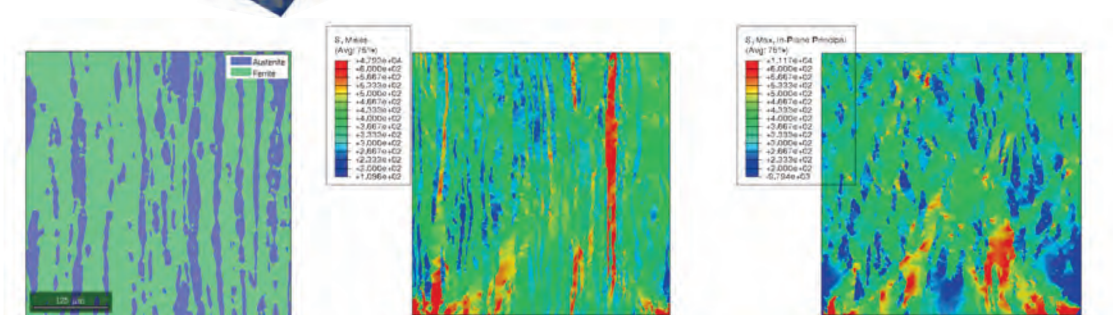

Figure 2. Duplex microstructures

T2 Supporting doctoral project modeling development

A lot of effort was directed toward supporting the PhD thesis work related to the other projects in BSA. The research work was carried out in collaboration with experimental and modeling and simulations groups for better output. As an example, the microstructures of the steels during the continuous annealing cycle were modeled based on orientation distributions measured after the heat treatments. A model was developed to reconstruct the high-temperature microstructure from the room temperature images, to optimize the temperatures used for the continuous annealing cycle.

A new methodology was developed to reconstruct high-temperature microstructures before quenching.

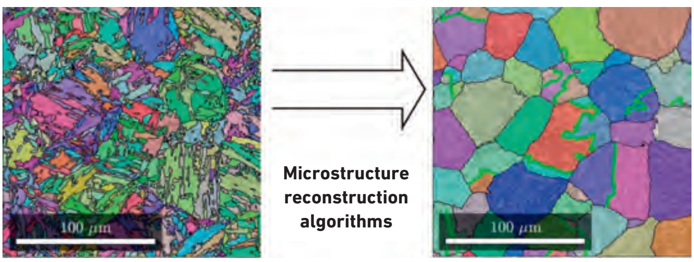

Figure 3. **a) Room-temperature microstructure after heat treatment; and b) reconstructed high-temperature microstructure prior to quenching**

Another example is the experimental-numerical estimation of the fatigue life of high-strength steels. The modeling approach was supported by experiments that were critical for the calibration of the model. After the calibrations, the model predictions were compared to established analytical approximations such as Neuber's rule and the strain energy density method. The newly developed finite element-based method gave the most accurate predictions of fatigue life, providing an effective tool for fatigue life analysis of the studied high-strength steels.

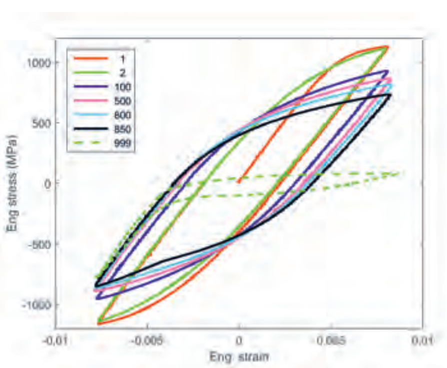

Figure 4. **Experimental calibration of the material model**

A thermodynamic-kinetic tool was developed to simulate solidification microstructures in steels that is used for developing new steel grades.

IDS is a thermodynamic-kinetic-empirical tool that simulates solidification and microstructure development in steels, from liquid state down to room temperature, and in steelmaking from continuous casting to hot rolling. IDS applies an extensive databank containing thermodynamic, diffusion, and material property data, all optimized by a huge number of experimental measurements. IDS has been validated by numerous solidification-related temperature, solute partition, and ferrite content measurements. The IDS databank has been further extended and now it includes the following elements: C, Si, Mn, P, S, Cr, Ni, Mo, Al, Cu, N, Nb, Ti, V, Ca, B, O, Ce, Mg, H. The composition ranges have also been extended for more advanced steels. IDS also calculates inclusions, precipitates, and material data. Many new compounds are now available, and material data includes enthalpy, thermal conductivity, density, liquid viscosity, surface tension, elastic modulus, creep rates, and stacking fault energy. SCALE is a sub-model of the IDS tool, which simulates oxide formation at the steel strand surface. The scale tool simulates the metal loss and oxide weight gain at the strand surface, as a function of time, temperature, and oxygen pressure. It also gives an estimation for the fractions of different oxides formed, as well as their characterization (whether the oxide is protective or not). IDS is used for development work on new steel grades, as well as for the design and optimization of production/process parameters for high-quality steels to avoid defect formation. An online version can be used for quality prediction. The online version is undergoing industrial testing in the DIMECC SIMP program.

This task further develops fatigue life modeling of high-performing welds. This is needed because the existing fatigue methods do not distinguish the crack initiation phase from crack propagation. Crack initiation is highly dependent on the material microstructure and its mechanical properties. Furthermore, existing models are continuum-based, not including the influence of the microstructure. Material microstructure can be included in the simulation indirectly by defining the homogenization unit based on microstructural dimensions. To make this possible, this task develops material characterization methods for complex heterogeneous welded microstructures (Lehto et al. 2016). The grain size characterization is utilized for defining the size of the homogenization unit utilized in the strain-based continuum fatigue modeling. Fatigue crack initiation and growth are modeled for an arbitrary weld shape, and have been successfully applied to model the weld shape effect and fatigue behavior of high-performing welded joints (Remes et al. 2016). The fatigue strength of a joint was found to be strongly influenced by the weld geometry. In high-performance welds, crack

Weld shape is critical for fatigue strength – the novel model makes it possible to optimize it.

initiation took up to 99% of the entire fatigue life, highlighting the need for consideration of crack initiation.

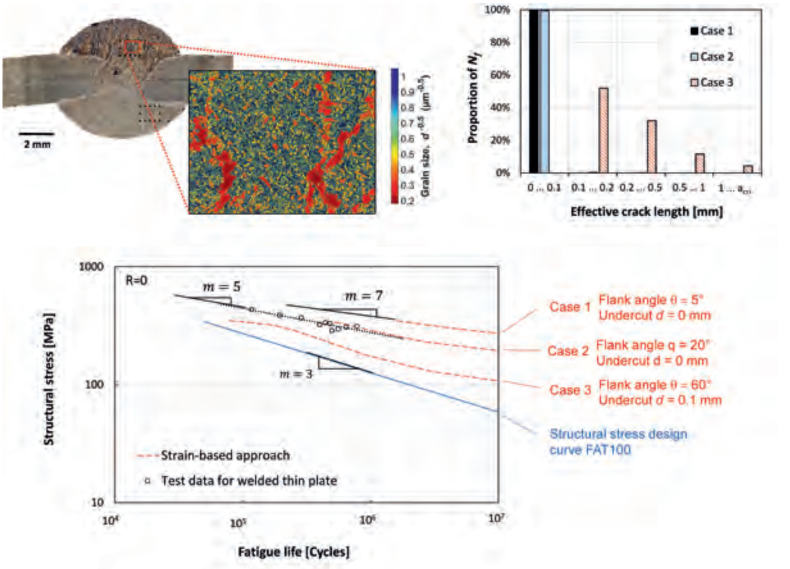

Figure 5. **Newly developed fatigue life model based on true microstructures of the material**

T3 Building of generic modeling toolkits

Modeling toolkits were developed to support the numerical studies of individual projects and subprojects in BSA. The focus of this development was on corrosion (P1), fatigue, fracture, wear and tribocorrosion (P2), and mechanical properties of duplex microstructures (P3). In collaboration with P1 and P2, a framework was set to provide a basis for modeling interactions between environmental and mechanical loading, as in the case of tribocorrosion. In P2, the focus was largely on modern very high-strength steels and microstructure-founded modeling of their material properties and specific performances, especially behavior in demanding wear environments. The developments serve the modeling of mechanical properties in general, whether the interest is in, for example, the cumulative response to fatigue or evaluating fracture behavior based on microstructural stress-strain states.

A representative example of modeling toolkit development is the modeling of abrasive wear. This toolkit enables quite realistic modeling of the wear, loading, and material response of the studied steels in these two selected cases. The toolkit com-

A modeling toolkit developed to model wear, loading, and material response in abrasive wear – provides quantitative design criteria for material selection.

bines the microstructure information, crystal plasticity, loading conditions, and so on. The wear rate, mass loss, and surface damage can be extracted from the model for different microstructures. Local phenomena can also be estimated and visualized for better understanding of the wear mechanisms. The results obtained with this modeling toolkit improve materials selection and give quantitative design criteria for components under the given conditions. For material producers, the information obtained from the simulations gives valuable information for process control for the production of optimized microstructures.

a)

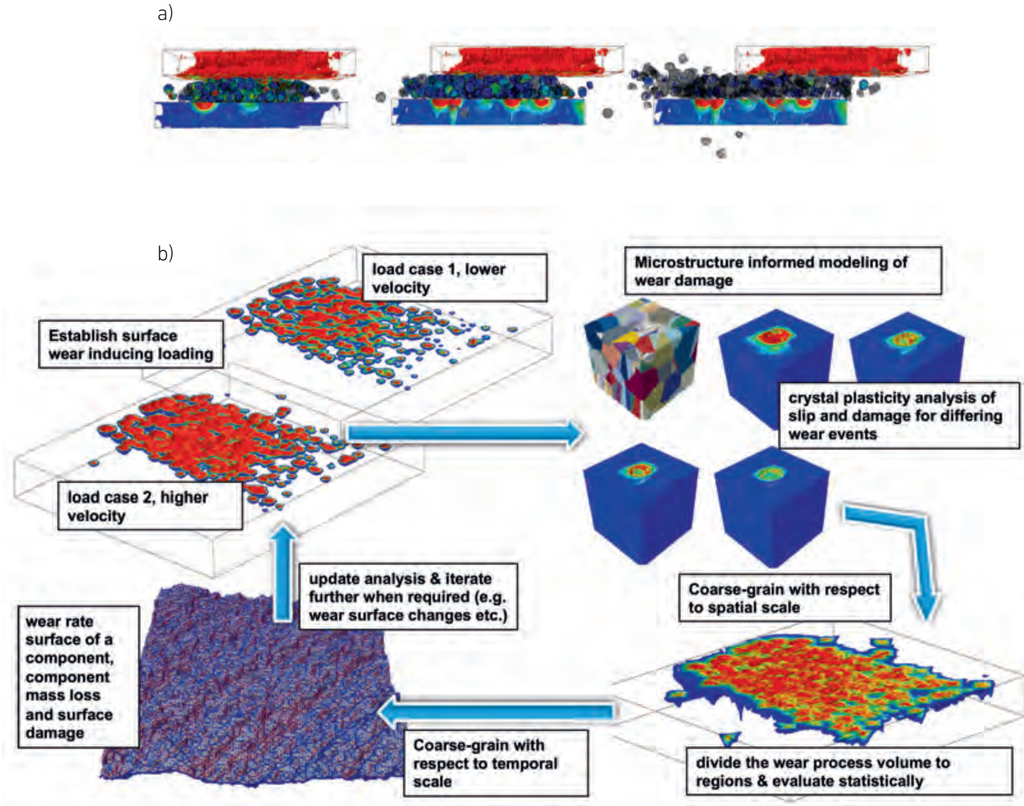

Figure 6. **a) Sliding abrasion model and b) modeling toolkit for abrasive wear**

T4 Characterization for modeling input data

Extensive microstructural and mechanical characterization of various steels was carried out during the project. The majority of the results are reported in the scientific publications and reports of the other projects. Therefore, only some highlights that are not published elsewhere are presented here.

Figure 7. **Compressive failure of the rock at high confinement**

Figure 8. **Compressive failure of the rock at low confinement**

The modeling of the fracture and fragmentation of granite rock was tested to support the modeling efforts of rock fragmentation in the jaw crusher. Rock fracture is highly sensitive to the loading rate and confining pressure, which both vary significantly during the rock crushing process. The compressive strength of the rock was characterized in a wide range of confining pressures and loading rates, and the experimental results were used to generate a material model for the rock. The model was then used to simulate rock behavior in the jaw crusher. This model enables accurate estimation of the rock fragmentation and fragment size distributions, but also the loading and response that the crushing of the rock causes on the jaws themselves. This experimental work was carried out in collaboration with the Norwegian NEXTDRILL consortium, focusing on deep drilling for geothermal heat, and Purdue University (USA), where the high rate confining tests were carried out. The material data obtained in this work has also been used for modeling material behavior during impact loading and simulation of percussive drilling.

Experimental data combining various loading conditions was used to develop models for rock fragmentation in jaw crushers and in percussive drilling.

$$\sigma_1 - \sigma_3 = \sigma_{UC}\left(m\frac{\sigma_3}{\sigma_{UC}}\right)^{1/2}$$

$$\sigma_1 - \sigma_3 = \sigma_{UC} + B{\sigma_3}^{n}$$

Hoek-Brown failure criterion and the newly developed failure criterion for high confinement and high rate impacts

A material model was also developed for estimating the strain rate-dependent plasticity of metastable austenitic stainless steel. The development of the model required extensive mechanical testing and characterization of the microstructures of the material before and after deformation. The developed constitutive model can take into account the deformation history of the material and the strain-induced phase transformations, yielding accurate predictions of material behavior. The model was also validated by experiments and was shown to give a realistic description of the material behavior with a reasonable number of experimental constants. This model is a remarkable step toward quantitative understanding of the micromechanisms controlling the plasticity of metastable austenitic stainless steels, as well as toward design guidelines for both optimization of the microstructures and use of the material.

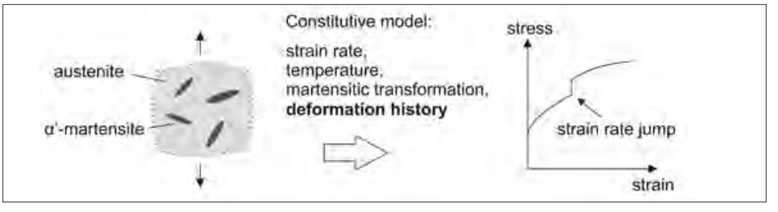

Figure 9. **Description of the constitutive model**

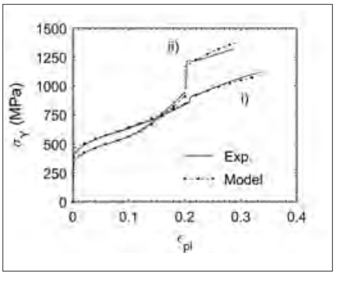

Figure 10. **Experimental verification of the model**

T5 Testing and validation

Testing and validation of the models and simulations was carried out throughout the project. The thermodynamic and diffusional software ThermoCalc and Dictra were validated concerning the calculation of carbon solubility in ferritic stainless steel. Fracture, fatigue, and wear behavior of various materials were studied, and a new methodology was developed for the analysis of the material behavior. In particular, image-based measurements such as Digital Image Correlation (DIC) and infrared measurements were developed to match the research needs of the projects. These measurements not only give new information about the material behavior, but can also be used for verification of the simulation models. The strain information obtained with DIC can be compared with the simulation results for quantitative verification of the material model. Some examples of the result highlights are given in the following.

A methodology for simultaneous optical strain analysis and temperature measurements was developed to analyze strain localizations and adiabatic heating at higher strain rates. These are totally new kinds of measurements as no similar work has been presented previously. The results combine the internal mechanical and thermal responses of the material, and therefore give a solid basis for model verification and separation of cross-linked variables, such as strain rate and temperature.

Simultaneous deformation and temperature measurements enable verification of thermal-viscoplasticity models.

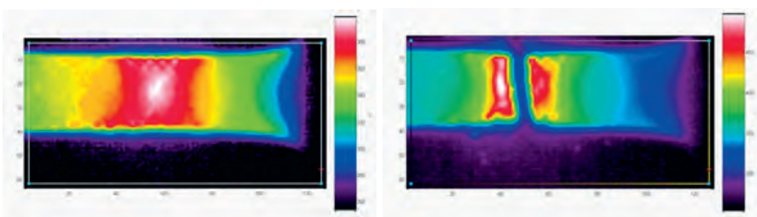

Figure 11. Full-field temperature profile of a tensile specimen during a high-rate test obtained by a high-speed IR camera

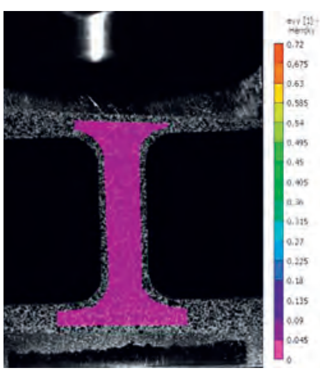

Figure 12. Deformation analysis of the tension specimen by Digital Image Correlation

Another example of testing and validation activities is the developed material model for the rock materials and its experimental validation. An experimental methodology was developed to change the microcrack distribution of a Brazilian Disc rock sample using heat shocks. The surface crack networks were experimentally characterized on the surface, and the interior crack distributions were modeled using an embedded discontinuity approach. The modeling framework was evaluated by comparing the strain distributions obtained in the simulations to those obtained experimentally with the developed non-contacting optical methods.

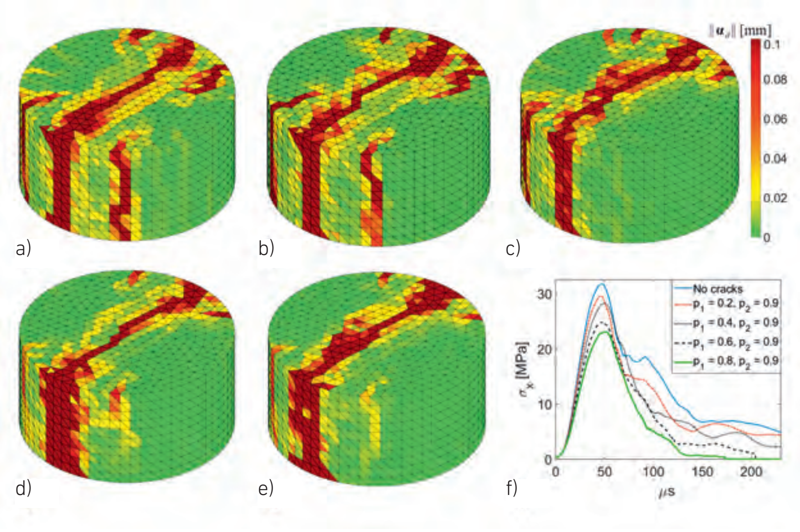

Figure 13. Simulated damage patterns of a heat-shocked Brazilian disc sample

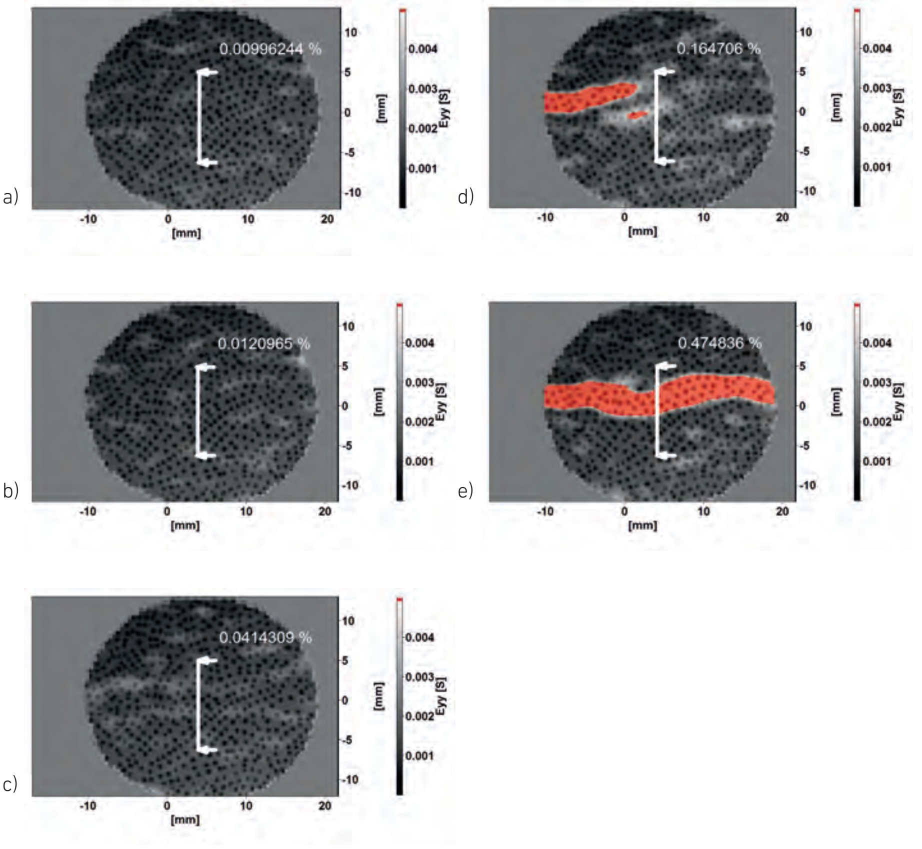

Figure 14. Damage on the surface of the Brazilian Disc sample obtained by Digital Image Correlation

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 on supporting primarily the PhD theses of those students who had realistic possibilities to graduate within the shortened duration of the BSA program. Despite this, the obtained results of 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 by 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 the structure-property-performance relationships of the most important construction 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. Some research methods and developed new materials have already been used in other international projects. After the project, a global network of colleagues and collaborators also exists, ready to plan new state-of-the-art research projects.

Further information

KEY PUBLICATIONS:

Lindroos, M. Experimental and Numerical Studies on the Abrasive and Impact Behavior of Wear Resistant Steels. PhD Thesis. Tampere University of Technology, 2016.

Nyyssönen, T. Quenching and Partitioning of High-Aluminum Steels. PhD Thesis. Tampere University of Technology, 2017.

Smith, J., Kuokkala, V-T., Seidt, J., Gilat, A. Full-Field Temperature and Strain Measurement in Dynamic Tension Tests on SS304. In the Proceedings of the SEM Annual Conference series,2016.

Dabiri, M., Isakov, M., Skriko, T., Björk, T. Experimental Fatigue Characterization and Elasto-Plastic Finite Element Analysis of Notched Specimens made of Direct-Quenched Ultra-High-Strength Steel. Journal of Mechanical Engineering Science (2016), vols. 203–210.

Lehto, P; Romanoff, J; Remes, H; Sarikka, T. Characterisation of local grain size variation of welded structural steel, Welding in the World, 2016; 60: 673–688.

Remes, H; Romanoff, J; Lillemäe, I; Frank, D; Liinalampi, S; Lehto, P; Varsta P. Factors affecting the fatigue strength of thin-plates in large structures. Special issue on: Progress in Fatigue Life Estimation of Weldments. International Journal of Fatigue, 2016.

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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 (OU); 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, McGills 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 Cr2O3-TiO2 thermal spray coatings, VTT, McGills 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.

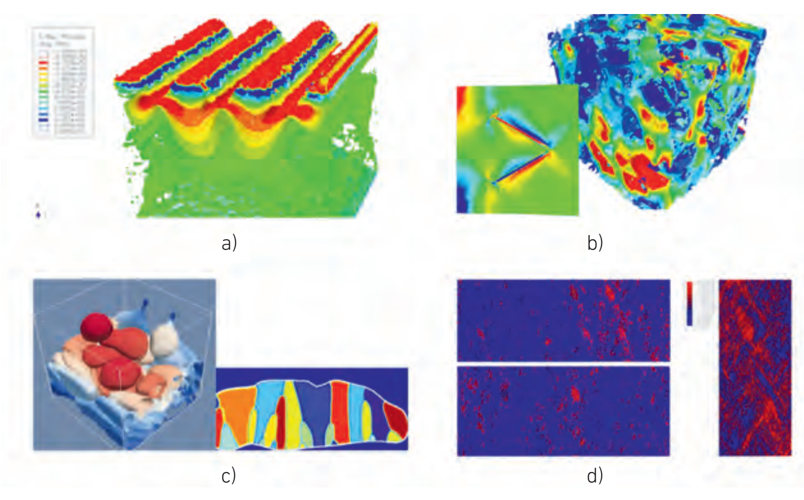

Figure 1. **Novel software tools for material digitalization and performance simulation developed in the FunMode project: a) an integrated topography-microstructure fractal multiscale surface model, b) a thermodynamic and phase field-based multiscale model for WC-Co cemented carbides, c) a process-microstructure-properties 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**

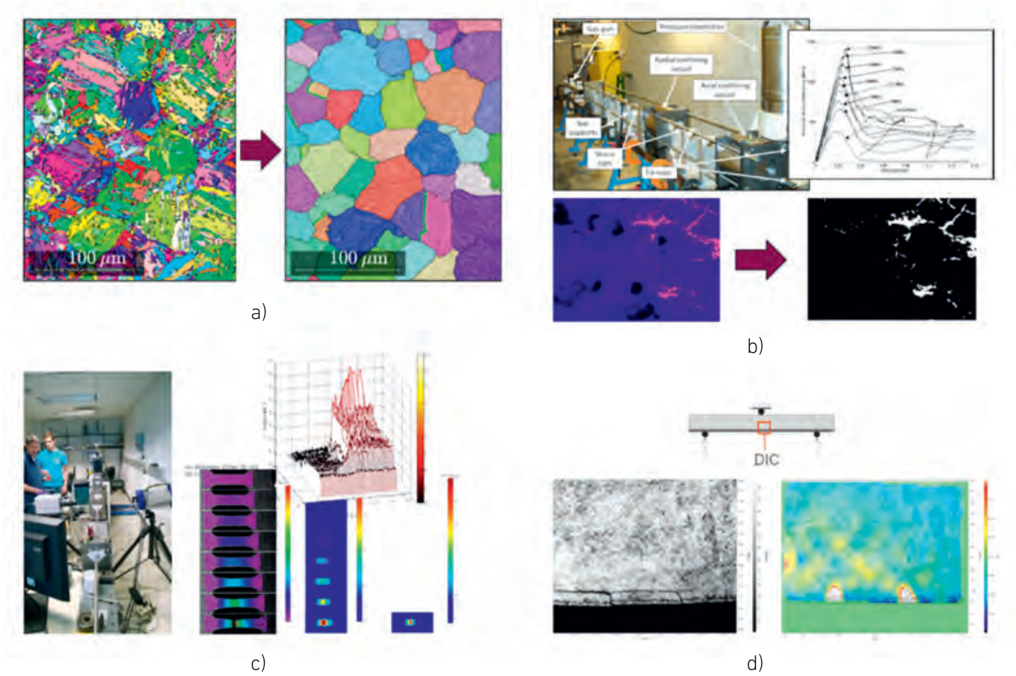

Figure 2. Novel characterization, measurement and testing techniques for digital material data generation developed in the FunMode project: a) reconstruction of austenite microstructure and orientations, b) a model for predicting the strength of granite at dynamic loading, c) synchronous full-field measurement 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*

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List of publications

BSA P1 SP1: Green processes (GPRO)

Aronen, J., Influence of chemical composition on crevice corrosion of some ferritic stainless steels, MSc thesis in Outokumpu, 2015.

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

Lindgren, M., Siljander, S., Suihkonen, R., Pohjanne, P., Vuorinen, J. Erosion-corrosion resistance of various stainless steel grades in high-temperature sulfuric acid solution, Presentation in NordTrib 2016 symposium 6/2016.

Raunio M., Basic approaches and goals for crevice corrosion modelling, RESEARCH REPORT VTT-R-02078-15, 2015.

Raunio M., Properties and monitoring of precipitates and related corrosion, RESEARCH REPORT VTT-R-02118-15, 2015. (together with BSA/P1SP3-DETER).

BSA P1 SP2: Productive boiler (Proiler)

Pitkänen V. Failure Mechanisms of Furnace Tube Materials in Porvoo Oil Refinery, Master's thesis 2014.

Sarikka T., Romu J. and Hänninen H. Early Stage Oxidation Behavior of Al- and Si-alloyed stainless steels as well as Ni-based alloy in air at Elevated Temperatures, to be published.

Sarikka T., Romu J., Hänninen H., Tuurna S., Pohjanne P. Performance of FeCrAl/Si- and Ni-based alloys in simulated biofuel environment, to be published.

Tuurna S., Pohjanne P. Monitoring and in-service experiments on plants. Baltica X International Conference on Life Management and Maintenance for Power Plants 2016.

Tuurna S., Pohjanne P. Applicability of different electrochemical measurement systems for high temperature corrosion monitoring. to be published.

Tuurna S., Pohjanne P., T. Kinnunen. Material optimization with corrosion probe measurements, EuroCorr 2017 Prague, Sept 2017.

Tuurna S., Romu J., Hänninen H., Mahanen J., Puikkonen T. Käyttövarmuutta kattiloihin uusilla materiaalivaihtoehdoilla, Hitsaustekniikka 1/2017.

Yli-Olli S., Auerkari P., Tuurna S., Pohja R., Holmström S. Lifetime assessment: modelling of steamside oxidation, Baltica X International Conference on Life Management and Maintenance for Power Plants 2016.

Yli-Olli S., Tuurna S., Auerkari P., PenttiläS. Evaluating the effect of cold work on supercritical oxidation of boiler tube materials. 8th International Conference on Advances in Materials Technology for Fossil Power Plants, Portugal 2016.

BSA P1 SP3: Deposition, corrosion and fouling in cooling and fire protection water cycles – mechanisms, monitoring and prevention (DETER)

Pylväläinen, H. 2015. Corrosion phenomena of stainless steels and brass in stagnant water environment. Master's thesis. Aalto University, School of Chemical Technology.

Rajala, P., Sohlberg, E., Priha, O., Tsitko, I., Väisänen, H., Tausa, M., Carpén, L. Biofouling on Coated Carbon Steel in Cooling Water Cycles Using Brackish Seawater. J. Mar. Sci. Eng. 2016, 4, 74.

Rajala, P., Bomberg, M., Huttunen-Saarivirta, E., Priha, O., Tausa, M., Carpén, L. Influence of Chlorination and Choice of Materials on Fouling in Cooling Water System under Brackish Seawater Conditions. Materials 2016, 9, 475.

Raunio M, Rajala P, Carpén L, Huttunen-Saarivirta E. Biofouling and corrosion on stainless steels in Baltic sea water environment: a cooling water pilot study, Baltica X conference 2016. Life Management and Maintenance for Power Plants, 7 – 9 June 2016, Helsinki-Stockholm-Helsinki. In: Baltica X. VTT Technology: 261, VTT, 17 p.

Rajala P, Huttunen-Saarivirta E, Carpén L. Biofouling, deposition and corrosion in cooling water cycles using brackish seawater, 18th ICMCF conference 2016, poster presented.

Rajala, Pauliina, Raunio, Maija, Sohlberg, Elina, Priha, Outi, Carpén, Leena. 2015. The effect of chlorination on microbially induced corrosion of carbon steel in cooling water system under brackish seawater conditions. 16th Nordic Corrosion Congress, NCC 2015, 20 – 22 May 2015, Stavanger, Norway. Proceedings.

Raunio, M. Properties and monitoring of organic and inorganic precipitates and related corrosion. Research Report VTT-R-02118-15.

Raunio, M. Basic approaches and goals for crevice corrosion modelling. - Research Report VTT-R-02078-15. (together with BSA/P1SP1GPRO).

BSA P2 SP1 (Highmarine) + (EXTREMEST) = Marine and offshore

Lappi, J. "Utilization Potential of High Strength Steel in Fatigue Loaded Floating Production Storage and Offloading Unit Structures", Master's Thesis, Aalto University School of Engineering, Department of Applied Mechanics, 2015.

Lehtimäki, E. "Effect of weld microstructure on fatigue and fracture of ultra-high-strength steel plates", Master's thesis, Aalto University School of Engineering, Department of Mechanical Engineering, 2016.

Lehto, P; Romanoff, J; Remes, H; Sarikka, T. Characterisation of local grain size variation of welded structural steel, Welding in the World, 2016; 60: 673–688.

Liinalampi, S., Remes, H., Lehto, P., Lilllemäe, I., Romanoff, J. and Porter, D., "Fatigue strength analysis of laser-hybrid welds in thin plate considering weld geometry in microscale", International Journal of Fatigue, Vol. 87, 2016, pp. 143–152.

Lillemäe, I.; Remes, H.; Liinalampi, S.; Itävuo, A., "Influence of weld quality on the fatigue strength of thin normal and high strength steel butt joints", Welding in the World, Vol. 60, 2016, pp. 731–740.

Lillemäe, I.; Liinalampi. S.; Lehtimäki, E.; Remes, H.; Romanoff, J.; Lehto, P. "Fatigue strength of high-strength steel plates on very high-cycle fatigue regime", Marine Structures, 2017, (to be submitted).

Mikkola, E., Marquis, G. B., Lehto, P., Remes, H., Hänninen, H. "Material characterization of high-frequency mechanical impact (HFMI)-treated high-strength steel", Materials and Design, Vol 89, 2016 pp. 205–214.

Mikkola, E; Remes, H; "Allowable stresses in high-frequency mechanical impact (HFMI)-treated joints subjected to variable amplitude loading", Welding in the World, Vol 61, 2017, pp. 125–138. Ref a.

Mikkola, E; Remes, H; Marquis, G, "A finite element study on residual stress stability and fatigue damage in high-frequency mechanical impact (HFMI)-treated welded joint". International Journal of Fatigue, Vol 94, 2017, pp. 16–29. Ref b.

Peltonen, M., M., "Weldability of high-strength steels using conventional welding methods", Master's thesis, Aalto University, School of Engineering, 2014.

Remes, H., Korhonen, E., Lehto, P., Romanoff, J., Niemelä, A., Hiltunen, P. and Kontkanen, T., "Influence of surface integrity on the fatigue strength of high-strength steels", Journal of Constructional Steel Research, Vol. 89, 2013, pp. 21–29.

Remes, H., Peltonen, M., Seppänen, T., Kukkonen, A., Liinalampi, S., Lillemäe, I., Lehto, P., Hänninen, H., Romanoff, J., Nummela, S., "Fatigue strength of welded extra high-strength and thin steel plates based on nominal and structural hot-spot stress approaches", MARSTRUCT 2015, 5th International Conference on Marine Structures, March 25 – 27, 2015, Southampton UK.

Remes, H.; Jelovica, J.; Romanoff, J.; Lehto, P.; Liinalampi, S. "Fatigue strength modelling of high-performance welds using local approaches", PRADS 2016, International Symposium on Practical Design of Ships and Other Floating Structures, 4th – 8th September, 2016, Copenhagen, Denmark.

SMART MARITIME TECHNOLOGY SOLUTIONS – Strategic Research Agenda for The Finnish Maritime Cluster 2014–2020, Finnish Marine industries' Research Committee, 2013.

Wallin, K., Karjalainen-Roikonen, P. and Pallaspuro, S., "Estimating Low Temperature Fracture Properties for Very High Strength Steels", TPC 2015.

Wallin, K., Karjalainen-Roikonen, P. and Suikkanen, P., "Crack Arrest Toughness Estimation for High Strength Steels from Sub-Sized Instrumented Charpy-V Tests", ISOPE 2016. Ref. a.

Wallin, K., Karjalainen-Roikonen, P. and Suikkanen, P., "New interpretations of the Charpy V test", Baltica X Conference.

Wallin, K., Karjalainen-Roikonen, P. and Suikkanen, P., "Sub-sized CVN specimen conversion methodology", 21st European Conference on Fracture, ECF21, 20–24 June 2016, Catania, Italy. Ref. b.

Wallin, K., Karjalainen-Roikonen, P., Pallaspuro, S. and Suikkanen, P., "Applicability of the Master Curve Method to Ultra High Strength Steels", Proceedings of the ASME 2015 Pressure Vessels & Piping Division Conference PVP2015 July 19–23, 2015, Boston, Massachusetts, USA, PVP2015-45554 DRAFT.

Wallin, K., Pallaspuro, S., Valkonen, I., Karjalainen-Roikonen, P. and Suikkanen, P., "Fracture properties of high performance steels and their welds", Engineering Fracture Mechanics, Vol. 135, pp. 2015, pp. 219–231.

Yıldırım, H.C., "Review of fatigue data for welds improved by tungsten inert gas dressing", International Journal of Fatigue, Vol. 79, 2015, pp. 36–45.

Yildırim, H.C., Leitner, M., Marquis, G.B., Stoschka, M., and Barsoum, Z., "Application studies for fatigue strength improvement of welded structures by high-frequency mechanical impact (HFMI) treatment", Engineering Structures, Vol. 106, 2016, pp. 422–435.

Yıldırım, H.C., Marquis, G. and Sonsino, C.M., "Lightweight design with welded high-frequency mechanical impact (HFMI) treated high-strength steel joints from S700 under constant and variable amplitude loadings", International Journal of Fatigue, Vol. 91, 2016, pp. 466–474.

BSA P2 SP2 Task1: Sustainable Multi-resistance Steel Structures (SuMuReSS)

Ahola A., Nykänen T., Björk T. Effect of loading type on the fatigue strength of asymmetric and symmetric transverse non-load carrying attachments. Fatigue & Fracture of Engineering Materials & Structures, 2016. 13 p. doi: 10.1111/ffe.12531.

Amraei M., Dabiri M., Björk T., Skriko T. Effects of Workshop Fabrication Processes on the Deformation Capacity of S960 Ultra-high Strength Steel. Journal of Manufacturing Science and Engineering, 2016. Vol. 138: 12. 13 p. doi: 10.1115/1.4033930.

Amraei M., Skriko T., Björk T., Zhao X-L. Plastic Strain Characteristics of Butt-Welded Ultra-High Strength Steel (UHSS). Thin-Walled Structures, 2016. Vol 109, doi: 10.1016/j.tws.2016.09.024.

Björk T., Penttilä T., Nykänen T. Rotation capacity of fillet weld joints made of high-strength steel. Welding in the World, 2014. Vol. 58, Issue 6.

Björk T., Valkonen I., Kömi J., Idren H. Capacity of a Welded Structure of Direct-Quenched Ultra-High-Strength Structural Steels. SAE Brazil international Suspension and Trailer, 2014. Vol 3014-36-0031.

Björk T., Ahola A., Nykänen T. Punching shear capacity of T-joint made of high-strength steel. Welding in the World, 2016. Vol. 60: 2. pp. 315–326. doi: 10.1007/s40194-015-0292-6.

Björk T., Forsström L., Ahola A., Nykänen T. Punching shear capacity of T-joint made of high-strength steel. IIW-doc XV-1471-14. 2014.

Björk T,. Nykänen T., Valkonen I. On the critical plane of axially loaded plate structures made of ultra high strength steel. Welding in the World, 2016.

Björk T., Tuominen N., Lähde T. Effect of the secondary bending moment on K-joint capacity. ISTS15,15th International Symposium on Tubular Structures, 2015.

Dabiri M., Björk T. Simulation of Cyclic Stress-Strain Behavior of S960 at Weld Toe by means of Finite Element Method. International Journal of Advancements in Mechanical and Aeronautical Engineering, 2014. Vol. 1, Issue 2, Pages 30–34.

Dabiri M., Skriko T., Björk T. Preparation of S960QC steel specimens for fatigue testing: Effect of machining and post-treatments on surface residual stress. International Journal of Advancements in Mechanical and Aeronautical Engineering – IJAMAE, 2015. Vol. 2: 2. pp. 243–246.

Dabiri M., Laukkanen A., Björk T. Fatigue micro-crack nucleation modeling; A survey of the state of the art. International Review of Mechanical Engineering, 2015. Vol. 9: 4. doi: 10.15866/ireme.v9i4.6231.

Dabiri M., Isakov M., Skriko T., Björk T. Experimental fatigue characterization and elasto-plastic finite element analysis of notched specimens made of direct-quenched ultra-high-strength steel. Proc IMechE Part C: Journal of Mechanical Engineering Science, 2016. Published online before print. 18 p. doi: 10.1177/0954406216661210.

Dabiri M., Skriko T., Amraei M., Björk T. Effect of Side Grooves on Plane Stress Fracture Behavior of Compact Tension Specimens Made of Ultra-High Strength Steel. Key Engineering Materials, 2016. Vol. 713. pp. 159–162. doi: 10.4028/www.scientific.net/KEM.713.159.

Dabiri M., Ghafouri M., Rohani Raftar H., Björk T. Neural network-based assessment of the stress concentration factor in a T-welded joint. Constructional Steel Research, 2016. Vol 128 doi: 10.1016/j.jcsr.2016.09.024.

Hämäläinen O-P., Björk T. Fretting fatigue phenomenon in bolted high-strength steel plate connections. Nordic Steel Construction Conference (NSCC), 2015. 5 p.

Hämäläinen O-P., Björk T. Fretting fatigue phenomenon in bolted high-strength steel plate connections. Steel Construction – Design and Research, 2015. Vol. 8: 3. pp. 174–178. doi: 10.1002/stco.201510021.

Koskimäki M., Tuominen N., Björk T. Fatigue Strength of Ferritic Stainless Rectangular Hollow Section T-joints as Welded and Post Treated Conditions. IIW Conference, Helsinki, 2015.

Neuvonen R., Skriko T., Björk T. Suojausterästen materiaalimallit. Rakenteiden Mekaniikka, 2016.

Neuvonen R. Effects of Laser Weld Parameters on the Strength Properties of Weld Joints in Armour Steel. IIW Conference, Helsinki, 2015.

Nykänen T., Björk T., Mettänen H., Ilyin A.V., Koskimäki M. Residual strength at -40°C of a pre-cracked cold-formed rectangular hollow section made of ultra-high-strength steel – An engineering approach. Fatigue and Fracture of Engineering Materials and Structures, 2014. Vol. 37, Issue 3. pp. 325–334.

Nykänen T., Björk T. A new proposal for assessment of the fatigue strength of steel butt-welded joints improved by peening (HFMI) under constant amplitude tensile loading. Fatigue & Fracture of Engineering Materials & Structures, 2016. Vol. 39: 5. pp. 566–582. doi: 10.1111/ffe.12377.

Nykänen T., Björk T. A new proposal for assessment of the fatigue strength of steel butt-welded joints improved by peening. IIW Conference 2015, Helsinki. 2015.

Nykänen T., Björk T. Assessment of fatigue strength of steel butt-welded joints in as-welded condition – Alternative approaches for curve fitting and mean stress effect analysis. Marine Structures, 2015. Vol. 44. pp. 288–310. doi: 10.1016/j.marstruc.2015.09.005.

Nykänen T, Mettänen H, Björk T, Ahola A. Fatigue assessment of welded joints under variable amplitude loading using a novel notch stress approach. International Journal of Fatigue. 10.1016/j.ijfatigue.2016.12.031. 2016.

Nykänen T, Mettänen H, Ahola A, Skriko T, Hämäläinen O-P, Björk T. 3R-menetelmän käyttö vaihtuva-amplitudisesti kuormitettujen hitsausliitosten väsymisanalysoinnissa. Rakenteiden Mekaniikka. Vol. 49, Issue 4, Pages 176–201. 2016 (in Finnish).

Pöllänen I., Björk T., Martikka H. Dynamical warping of tube branch welded joints. XII Finnish Mechanic Days, June 4–5, Tampere, 2015.

Peippo J., Björk T., Nykänen T. A novel method for fatigue assessment of steel plates with thermally cut edges. IIW Document XIII-2630-16. 2016. 17 p.

Ritakallio P., Björk T. Low-temperature ductility and structural behaviour of cold-formed hollow section structures- process during the past two decades. Steel Construction, 2014. Vol. 7, Issue 2.

Siltanen J., Skriko T., Björk T. Effect of the welding process and filler material on the fatigue behavior of 960 MPa structural steel at a butt joint configuration. Journal of Laser Applications, 2016. Vol. 28: 2. pp. 1–9. doi: 10.2351/1.4943993.

Siltanen J., Skriko T. Effect of the Welding Process and Filler Material on the Fatigue Behaviour of 960 MPa Structural Steel at a Butt Joint Configuration. 34th International Congress on Applications of Lasers & Electro-Optics (ICALEO), International congress on applications of lasers and electro-optics, 2015. 10 p.

Skriko T., Björk T. Welding metallurgy and fusion line softening of direct quenched ultra-high-strength steel. IIW Conference Helsinki, 2015.

Skriko T., Björk T., Nykänen T. Effects of weaving technique on the fatigue strength of transverse loaded fillet welds made of ultra-high-strength steel. Welding in the World. 2014. Vol. 58. Issue 3. pp. 377–387.

Skriko T., Ghafouri M., Björk T. Fatigue strength of TIG dressed ultra-high-strength steel fillet welded joints at high stress ratio. International Journal of Fatigue, 2016. Vol. 94, Part 1, doi: 10.1016/j.ijfatigue.2016.09.018.

Tasalloti H., Dabiri M., Kah P., Martikainen J. Effect of heat-input on the microstructure, mechanical and fatigue behavior of dissimilar weld of ultra-high strength steel and duplex stainless steel. Journal of Manufacturing Science and Engineering, 2016. (Accepted).

Tuominen N., Björk T. Ultimate Capacity of Welded Joints Made of High Strength Steel CFRHS. Eurosteel 2014: 7th European Conference on Steel and Composite Structures, 2014.

Doctoral dissertations

Peippo Juha, A modified nominal stress method for fatigue assessment of steel plates with thermally cut edges. Doctoral Thesis. Lappeenranta University of Technology, Department of Mechanical Engineering. Lappeenranta, 2015.

Master's Theses

Ahlfors Miro, Distortion and internal warping torsion of a double symmetric hollow section, 2015.

Ahola Antti, Effect of loading type on the fatigue strength of symmetric and asymmetric welded joints made of ultra-high strength steel, 2016.

Amraei Mohsen, Effects of Fabrication Processes on the Behavior of S960 Ultra-High Strength Steel (UHSS), 2015.

Barzin Behzad, Simulation and material calibration of ultra-high strength steel (UHSS) S960 welded joint under static tensile test utilizing finite element method (FEM), 2015.

Lehtoviita Lauri, Ultralujan teräksen kaarijuotto, 2016.

Mattila Mika, Investigation of the fatigue performance of welded duplex stainless steel, 2016.

Peltoniemi Teemi, The effect of stress concentration on the ultimate capacity of welded joints made of ultra-high strength steel, 2016.

Riski Jani, Low Cycle Fatigue of S960QC, 2017.

Salo Joel, Fatigue strength of welded joints in super-duplex stainless steel, 2016.

Suksi Tomi, Stresses of a boat trailer, 2015.

Ukkonen Eero, Convenience of scallops in plate structures, 2016.

BSA P2 SP2 Task 2: Surface fatigue and extreme load carrying capacity of gears (GeFa)

Aaltio, H-R. 2015. Grain size control in carburizing steel, Master of Science thesis, Tampere University of Technology.

Aaltio H-R, Hocksell E. 2015. Grain size control of carburizing steels, FIMECC Report.

Kattelus J. 2016. Upgrading measurement methods of a gear test rig. Master's thesis, Tampere University of Technology.

Kattelus J., Lehtovaara A., Miettinen J. 2016. Detection of gear pitting failure progression with on-line particle monitoring, Proc. of 17th Nordic Symposium on Tribology, Aulanko, Finland, June 14–17. Upgraded paper has been accepted to Tribology International.

Lahtivirta J. 2015. Modelling of spur gear contact using adaptive mesh. Master's thesis, Tampere University of Technology.

Lahtivirta J. & Lehtovaara A. 2016. Modelling of spur gear contact using a local adaptive finite element mesh, Finnish Journal of Tribology, 34(2016) 1–2, pp. 43–56.

Paattakainen, O., Elfström J., Kleemola, J., Soivio, K. 2017. Material technology plays a key role in improving torque density in wind turbine gearboxes. Conference for Wind Power Drives 2017, Aachen, Germany, March 7–8. (Conference presentation and proceedings).

Pitkänen, J. 2016. Commissioning of a large-scale bevel gear test rig, Master's thesis, Tampere University of Technology.

Soivio, K. & Elfström, J.. 2017. Materiaalitekniikka siivittää tuulivoimavaihteiston kilpailukykyä. Hitsaustekniikka, 69(2017)1, pp. 23–25.

Valtonen K. & Lehtovaara A. 2016. Kitka ja kuluminen haastavat koneensuunnittelijat, Materia 1(2016) pp. 29–30.

BSA P2 SP2 Task 3: Applications of high strength galvanized steel structures (APPGASS)

Järvinen H., Isakov M., Nyyssönen T., Järvenpää M., Peura P. The effect of initial microstructure on the final properties of press hardened 22MnB5 steels, Materials Science and Engineering: A, Vol. 676, 2016, pp. 109–120.

Järvinen H., Järn S., Lepikko E., Järvenpää M., Peura P. ZnFe Coated 22MnB5 Steels in Direct Press Hardening: The Relationships between Coating Structure and Process Parameters, Key Engineering Materials, Vol. 674, 2016, pp. 331–336.

Järvinen, H., Järvenpää, M., Peura, P. Bake hardening behavior of press hardened martensitic steels: effects of parent austenite grain size and carbon content. To be submitted in 4/2017.

Todoshchenko, O., Hänninen, H. Studies of Hydrogen Embrittlement, Technical report, Aalto University.

Järvinen, H., Peura, P., Järvenpää, M. Muottikarkaistavien teräslaatujen kehityslinjat, Ohutlevy-lehti, 1/2015.

BSA P2 SP2 Task 4: Virtual testing lab for novel materials and products (VILMA)

Hradil P., Fülöp L., Talja A. and Ongelin P 2016. Ductility requirements for structural details with stress concentration and diffuse necking. In: The International Colloquium on Stability and Ductility of Steel Structures – SDSS 2016, Timisoara: Universitatea Politehnica Timișoara.

Hradil P. and Talja A. 2015. True stress-strain relationship for finite element simulations of structural details under diffuse necking. In: Nordic Steel Construction Conference 2015, Tampere: Tampere University of Technology, 229–230.

Hradil, P. and Talja, A. 2016. Ductility limits of high strength steels, Research Report VTT-R-04741-16. Espoo: VTT Technical Research Centre of Finland, Ltd.

Hradil, P., Talja, A., Kurkela, J., Fülöp, L., Ongelin, P. Evaluation of ductility limits for structural steel design (in press), Journal of Constructional Steel Research, 2017.

Talja, A., Kurkela, J. and Hradil, P. 2015. FEM based virtual testing of HSS beams with flange holes, Research Report VTT-R-02326-15. Espoo: VTT Technical Research Centre of Finland, Ltd.

BSA P2 SP3: Optimization, prediction and design guidelines for improved wear life of novel steels and metallic multimaterials (O'DIGS)

Andersson, T., Laukkanen A., Lindroos, M., Cailletaud, G., Valtonen, K., Kuokkala, V.-T. & Kallio, M. 2017. Modelling of surface deformation and crushing events in the jaw crusher application. Submitted to Wear.

Andersson T., Lindroos, M., Laukkanen, Valtonen, K., Kuokkala, V.T., Mikkonen, P. 2017. Microstructural modeling of 2-body abrasion wear in mining equipment. To-be-submitted to Tribology International.

Ávalos del Río, A. 2015. Experimental Testing and Characterization of High Velocity Impacts on Novel Ultra High Strength Steels, Tampere University of Technology, Materials Science, Master of Science Thesis, 2015, 88 p.

Erdemir A. & Holmberg K. 2015. Energy consumption due to friction in motored vehicles and low-friction coatings to reduce it, In Sung Chul Cha and Ali Erdemir (eds.): Coating Technology for Vehicle Applications, Springer International Publishing 2015, pp 1–23.

Haiko, O., Miettunen, I., Porter, D., Ojala, N., Ratia, V., Heino, V., Kemppainen, A. 2016. Processing and Wear Testing of Novel High-Hardness Wear-Resistant Steel, Proceedings of Nordtrib 2016, submitted to Finnish Journal of Tribology.

Heino, V., Kallio, M., Valtonen, K. & Kuokkala, V.-T. 2016. The role of microstructure in high stress abrasion of white cast irons, Proceedings of Nordtrib 2016, 10 p., submitted to Wear.

Heino, V., Valtonen, K. & Kuokkala, V.-T. 2016. Sliding Wear of Quartzite and Granite Surfaces. Proceedings of Nordtrib 2014, 6 p.

Holmberg, K., Kivikytö-Reponen, P., Härkisaari, P., Valtonen, K. & Erdemir, A., 2017. Global energy consumption due to friction and wear in the mining industry, submitted to Tribology International.

Holmberg, K., 2016. Global impact of tribology on energy consumption, emissions and economy, Proc. 2016 International Conference on Engineering Tribology and Applied Technology, 4–6.11.2016, Taipei, Taiwan (invited plenary).

Holmberg, K., 2016. Global impact of friction and wear on energy consumption, costs and emissions in transportation and industry, Proc. PSE2016 – 15th International Conference on Plasma Surface Engineering, 12.9.2016, Garmisch-Partenkirchen, Germany (invited plenary).

Holmberg, K., 2016. Impact of friction and wear on global energy consumption in transportation and industry, Proc. LUBMAT – Lubrication, Maintenance and Tribology International Conference, 7–8.6.2016, Bilbao, Spain (invited plenary).

Holmberg, K., 2016. Global energy consumption due to friction in passenger cars, Proc. TTRF-TAIHO International Symposium on Automotive Tribology 2016, 6.4.2016, Nagoya, Japan (honorary lecture).

Holmberg, K., 2016. Friction and energy saving, Proc. 50th Anniversary of the "Jost Report" Celebratory Seminar, 2nd March 2016, Institution of Mechanical Engineers, London, UK (invited plenary).

Holmberg, K. & Erdemir A., 2014. Global impact of friction on energy use in transportation and industry, TRIBOBR 2014 2nd International Brazilian Conference on Tribology, Foz do Iguacu, Brazil, 3–5.11.2014 (invited plenary).

Härkisaari, P. & Holmberg, K. 2016. Wear and friction in mining equipment – three case studies. Book of abstracts, Nordtrib 2016.

Härkisaari, P. 2015. Wear and Friction Effects on Energy Consumption in the Mining Industry, Tampere University of Technology, Materials Science, Master of Science Thesis, 2015, 77 pages, 14 Appendix pages.

Jesser-Juhler, O. 2016. Paksujen polttoleikattujen teräslevyjen ultraäänitarkastus. Bachelor Thesis, Tampere University of Technology, 24 p.

Jokiaho, T., Saarinen, T., Santa-aho, S., Peura, P., Vippola, M. 2016. The Characterization of Flame Cut Heavy Steel – The Residual Stress Profiling of Heat Affected Surface Layer, Key Engineering Materials 674:103–108(2016).

Kiilakoski, J., Lindroos, M., Apostol, M., Koivuluoto, H., Kuokkala, V.-T. & Vuoristo, P. 2016. Characterization of high-velocity single particle impacts on plasma sprayed ceramic coatings, Journal of Thermal Spray Technology 25(6):1127–1137(2016).

Laakso, J. and Ojala, N. 2017. An all-in-one measurement tool for advanced materials characterization, Alicona focus variation magazine 3:2017.

Laukkanen A., Lindgren, M., Pinomaa, T., Lindroos, M., Andesson, T. 2017. Modelling of erosion-corrosion. To-be-submitted to Wear.

Laukkanen, A. 2016. ICME for design and tailoring of wear resistant solutions. Book of abstracts, Nordtrib 2016, p. 54.

Laukkanen, A. 2016. PSPP modeling for ICME of metallic, ceramic and composite materials. Book of abstracts, SIP-SI4M symposium, Tokyo, Japan 2016.

Laukkanen, A. 2015. Mesoscale modeling assisted materials-by-design concepts for novel metallic and composite materials. Book of abstracts, 6th WMRIF symposium 2015, Livermore, USA.

Lindroos, M. 2016. Experimental and Numerical Studies on the Abrasive and Impact Behavior of Wear Resistant Steels, Doctoral Thesis, Tampere University of Technology, Publication 1416, 244 p.

Lindroos, M., Laukkanen A., Andersson, T., Cailletaud, G., Valtonen, K., Kuokkala, V.-T. & Kallio, M. 2017. Multi-scale modelling of a jaw crusher application: microstructure-based crystal plasticity modelling of the material performance in mineral crushing conditions. Submitted to Wear.

Lindroos, M., Cailletaud, G., Laukkanen, A., Yastrebov, V., Kuokkala, V-T. 2017. Crystal plasticity modeling and characterization of the deformation twinning and strain hardening in Hadfield steels. Submitted to International Journal of Plasticity.

Lindroos, M., Laukkanen A., Kuokkala, V-T. 2017. Numerical modeling of deformation twinning in high manganese austenitic steel 3D microstructure aggregates. Submitted to International Journal of Engineering Science.

Lindroos, M., Laukkanen, A., Kuokkala, V-T. 2017. Microstructure based modeling of the strain rate history effect in Hadfield steels. To-be-submitted to Computational Materials Science.

Lindroos, M., Laukkanen, A., Kuokkala, V-T. 2017. Crystal plasticity model for shear banding in hot rolled steels. Submitted to Integrating Materials and Manufacturing Innovation.

Lindroos, M., Laukkanen, A., Andersson, T., Nyyssönen T., Kuokkala, V-T. 2017. Crystal plasticity modeling of strain hardening and localization in martensitic wear resistant steels. To-be-submitted to International Journal of Plasticity.

Ojala, N. 2017. Application oriented wear testing of wear resistant steels in mining industry. Doctoral Thesis, Tampere University of Technology.

Ojala, N., Valtonen, K., Antikainen, A., Kemppainen, A., Minkkinen, J., Oja, O. & Kuokkala, V.-T. 2016a. Wear performance of quenched wear resistant steels in abrasive slurry erosion, Wear 354–355:21–31(2016).

Ojala, N., Valtonen, K., Minkkinen, J. & Kuokkala, V.-T. 2016b. Edge effect in high speed slurry erosion wear tests of steels and elastomers, Proceedings of Nordtrib 2016, 13 p., submitted to Wear.

Penttilä, K. 2015. Työkaluterästen abrasiivinen kulumistestaus. Bachelor Thesis, Tampere University of Technology, 33 p.

Ratia, V., Valtonen, K., Kemppainen, A. & Kuokkala, V.-T. 2016a. The Role of Edge-Concentrated Wear in Impact-Abrasion Testing, Tribology Online 11(2):410-416(2016).

Ratia, V., Lindroos, M., Valtonen, K., Apostol, M. & Kuokkala, V.-T. 2016b. Impact behavior of martensitic steel at low temperatures, Proceedings of Nordtrib 2016, 9 p., submitted to Wear.

Ratia, V. 2016. Todellisuutta simuloiva kulumistestaus on haastavaa, mutta hyödyllistä. Materia 2:68–69(2016).

Ratia, V., Ojala, N., Valtonen, K. & Heino, V. 2016. Tuntemalla olosuhteet voit optimoida materiaalit kulutussovelluksiin. Promaint 3:16–20(2016).

Ripoll, M., Ojala, N. Katsich, C., Totolin, V., Tomastik, C., Hradil, K. 2016. The role of niobium in improving toughness and corrosion resistance of high speed steel laser hardfacings, Materials and Design 99:509-520(2016).

Terva, J. 2017. The effect of compression and sliding movement on the wear resistance of steels and crushing work in mineral crushing. Doctoral Thesis, Tampere University of Technology, Publication 1458, 130 p.

Terva, J., Valtonen, K., Siitonen, P. & Kuokkala, V.-T. 2016. Correlation of wear and work in dual pivoted jaw crusher tests, Proceedings of Nordtrib 2016, 17 p., submitted to Journal of Engineering Tribology.

Terva, J., Valtonen, K., Siitonen, P. & Kuokkala, V.-T. 2017. Effects of compression and sliding on the wear and energy consumption in mineral crushing, submitted to Wear.

Tiainen, T. & Valtonen, K.2015. Hard Rock (– ei Hallelujah, vaan) Tribology – Pohjoismainen kaivosteollisuuden kulumisongelmiin keskittyvä kurssi ja seminaari Tampereella, Materia 1:30–33(2015).

Tirkkonen, H. 2016. Grain refinement in austenitic manganese steels. Bachelor Thesis, Tampere University of Technology, 24 p.

Törmälä, R. 2016. Metallimatriisikomposiittien käyttö teollisuuden sovelluksissa. Bachelor Thesis, Tampere University of Technology, 23 p.

Valtonen, K., Kuokkala, V.-T. & Keltamäki, K. 2017. High-stress abrasion of wear resistant steels. Submitted to Tribology International.

Valtonen, K. 2017. Materiaaleja haastaviin kulumisolosuhteisiin. Materia 1:(2017).

Valtonen, K., Ratia, V., Ojala, N. & Kuokkala, V.-T. 2016. Comparison of laboratory wear test results with the in-service performance of cutting edges of loader buckets, Proceedings of Nordtrib 2016, 12 p., submitted to Wear.

Valtonen, K. & Lehtovaara, A. 2016. Kitka ja kuluminen haastavat koneensuunnittelijat, Materia 1:29–30(2016).

Vuorinen, E., Ojala, N., Heino, V., Rau, C. & Gahm, C. 2016a. Erosive and abrasive wear performance of carbide free bainitic steels – comparison of field and laboratory experiments, Tribology International 98:108–115(2016).

Vuorinen, E., Heino, V., Ojala, N., Haiko, O., Hedayati, A. 2016b. The effects of microstructure on erosive-abrasive wear behavior of carbide free bainitic and boron steels, Proceedings of Nordtrib 2016, 11 p., submitted to Journal of Engineering Tribology.

BSA P3 SP1: Novel Cast Materials (NOCMA)

Master's theses:

Jalava, K., Alternative cylinder head materials.

Karhula, L., Austemperability of solid solution strengthened ferritic ductile irons.

Okunnu, R., High strength solution-strengthened ferritic ductile cast iron.

Partanen, O., Optimization of solid solution strengthened ferritic ductile iron production by thermal analysis and solidification simulation.

Puustinen, E., Enhancing mechanical properties of solid solution strengthened ferritic spheroidal graphite cast iron with austempering heat treatment.

Future publications (2017):

Jalava, K., Soivio, K., Laine, J. and Orkas, J., Effect of silicon and microstructure on spheroidal graphite cast iron thermal conductivity at elevated temperatures.

Jalava, K., Soivio, K., Laine, J. and Orkas, J., Comparison of elevated temperature thermal conductivity of some gray, compacted graphite and nodular cast irons in as-cast and austempered conditions.

Jalava, K., Okunnu, R., Soivio, K., and Orkas, J., Influence of Cobalt addition on mechanical behaviour of solution strengthened ferritic ductile Iron.

Jalava, K., Vaara, J., Laine, J. and Orkas, J., Effect of ferrite and pearlite on spheroidal graphite cast iron Dynamic Strain Aging at elevated temperatures.

Karjalainen-Roikonen, P., Virta, J., Kokkonen P., Fracture toughness and microstructure of GJS with different heat treatments

BSA P3 SP2: Novel Super High Strength Steels (Super HSS)

Arola, A.-M.; Kaijalainen, A.; Kesti, V. (2016). The effect of surface layer properties on bendability of ultra-high strength steel. – ESAFORM 2016: Proceedings of the 19th International ESAFORM Conference on Material Forming. AIP Conference Proceedings 1769, 200024.

Arola, Anna-Maija; Kaijalainen, Antti; Kesti, Vili (2015). Evaluation of Bendability of Hot-Rolled S960 Grade Steel Using Optical Strain Measurements and FE-Modelling. – Key Engineering Materials 651–653, 610–616.

Challa, V. S. A.; Misra, R. D. K.; Somani, M. C.; Karjalainen, L. P. (2015). Interplay between grain size and austenite stability on the deformation behavior of high strength-high ductility combination austenite stainless steels. – Wire Journal International 48 (2), 68–72.

Challa, V. S. A.; Misra, R. D. K.; Somani, M. C.; Wang, Z. D. (2016). Strain hardening behavior of nanograined/ultrafine-grained (NG/UFG) austenitic 16Cr–10Ni stainless steel and its relationship to austenite stability and deformation behavior. – Materials science and engineering A: Structural materials: properties, microstructure and processing 649, 153–157.

Challa, V.S.A.; Misra, R.D.K.; Somani, M.C.; Wang, Z.D. (2016). Influence of grain structure on the deformation mechanism in martensitic shear reversion-induced Fe-16Cr-10Ni model austenitic alloy with low interstitial content: Coarse-grained versus nano-grained/ultrafine-grained structure. – Materials science and engineering A: Structural materials: properties, microstructure and processing 661, 51 – 60. http://doi.org/10.1016/j.msea.2016.03.002.

Haiko, Oskari; Miettunen, Ilkka; Porter, David; Ojala, Niko; Ratia, Vilma; Heino, Vuokko; Kemppainen, Anu (2016). Processing and Wear Testing of Novel High-Hardness Wear-Resistant Steel. The 17th Nordic Symposium on Tribology – NORDTRIB 2016. 2–11.

Hannula, Jaakko; Porter, David; Somani, Mahesh; Mehtonen, Saara (2016). Effect of molybdenum and niobium on the microstructures and mechanical properties of direct-quenched high-strength steel. 5th International Conference on Thermomechanical Processing. Milano, Italia, Associazione Italiana di Metallurgia, 5045.

Kaijalainen, A.; Suikkanen, P.; Porter, D. A. (2015). Effect of re-austenitization on the transformation texture inheritance. 17th International Conference on Textures of Materials (ICOTOM 17) : IOP Conference Series: Materials Science and Engineering. Skrotzki, W.; Oertel, C. G.. IOP Conference Series: Materials Science and Engineering 82. Bristol. 1–5, 012058.

Kaijalainen, Antti (2016). Effect of microstructure on the mechanical properties and bendability of direct-quenched ultrahigh-strength steels. Acta Universitatis Ouluensis. Series C, Technica 582. Oulu. Artikkeliväitöskirja. 116.

Kaijalainen, Antti Juhani; Liimatainen, Mia; Kesti, Vili; Heikkala, Jouko; Liimatainen, Tommi; Porter, David A. (2016). Influence of Composition and Hot Rolling on the Subsurface Microstructure and Bendability of Ultrahigh–Strength Strip. Metallurgical and Materials Transactions A 47 (8), 4175–4188.

Kaijalainen, Antti; Kesti, Vili; Arola, Anna-Maija; Liimatainen, Mia; Porter, David (2016). Microstructural investigation of strain localization, void formation and fracture mechanisms in ultrahigh-strength steel bending. Advancements in Theoretical and Applied Plasticity (Proceedings of PLASTICITY '16). Khan, Akhtar S. Maryland, USA. 40–42.

Kaijalainen, Antti; Liimatainen, Mia; Kesti, Vili; Anttila, Severi; Suikkanen, Pasi; Porter, David (2017). Effect of Red Scale on the Bendability of Ultra-high-Strength Strip Steel. – Materials Science Forum 879, 879–884.

Kaijalainen, Antti; Liimatainen, Mia; Kesti, Vili; Liimatainen, Tommi; Porter, David (2016). Influence of composition and hot rolling on the subsurface microstructure and bendability of ultrahigh-strength strip. Advancements in Theoretical and Applied Plasticity : Proceedings of PLASTICITY '16. Khan, Akhtar S. Maryland, USA, NEAT press. 37–39.

Kaijalainen, Antti; Suikkanen, Pasi; Karjalainen, Pentti; Porter, David (2016). Influence of subsurface microstructure on the bendability of ultrahigh–strength strip steel. – Materials science and engineering A: Structural materials: properties, microstructure and processing 654, 151–160.

Kesti, Vili; Kaijalainen, Antti; Mourujärvi, Juho; Ruoppa, Raimo (2015). Bendability and microstructure of Optim® 700 MC Plus. Proceedings of the 13th Nordic Steel Construction Conference. Tampere, Finland 23–25 September 2015. Tampere, 322.

Misra, R. D. K.; Challa, V. S. A.; Venkatsurya, P. K. C.; Shen, Y. F.; Somani, M. C.; Karjalainen, L. P. (2015). Interplay between grain structure, deformation mechanisms and austenite stability in phase-reversion-induced nanograined/ultrafine-grained austenitic ferrous alloy. – Acta Materialia 84, 339–348.

Misra, R. D. K.; Wan, X. L.; Challa, V. S. A.; Somani, M. C.; Murr, L. E. (2015). Relationship of grain size and deformation mechanism to the fracture behavior in high strength-high ductility nanostructured austenitic stainless steel. – Materials science and engineering A: Structural materials: properties, microstructure and processing 626, 41–50.

Nune, K.C; Somani, M.C.; Spencer, C.T.; Misra, R.D.K (2017). Cellular response of Staphylococcus aureus to nanostructured metallic biomedical devices : surface binding and mechanism of disruption of colonization. – Materials Technology 32 (1), 22–31.

Pohjonen, Aarne; Kaijalainen, Antti; Somani, Mahesh; Larkiola, Jari (2017). Analysis of Bainite Onset During Cooling Following Prior Deformation at Different Temperatures. – Computer Methods in Materials Science Vol. 17, 2017, No 1., pp. 30–35.

Pohjonen, Aarne; Somani, Mahesh; Pyykkönen, Juha; Paananen, Joni; Porter, David (2016). The onset of the austenite to bainite phase transformation for different cooling paths and steel compositions. – Key Engineering Materials 716, 368–375.

Rastegari, H.; Kermanpur, A.; Najafizadeh, A.; Porter, D.; Somani, M. (2015). Warm deformation processing maps for the plain eutectoid steels. – Journal of Alloys and Compounds 626, 136–144.

Rastegari,H; Kermanpur, A; Najafizadeh, A; Somani, M.C; Porter, D.A; Ghassemali, E; Jarfors, A.E.W (2016). Determination of processing maps for the warm working of vanadium microalloyed eutectoid steels. – Materials science and engineering A: Structural materials: properties, microstructure and processing 658, 167–175.

Saastamoinen, Ari; Kaijalainen, Antti; Porter, David; Suikkanen, Pasi (2016). Effect of titanium and nitrogen content on the microstructure, hardenability and mechanical properties of direct quenched and tempered ultra-high strength structural steel. 5th International Conference on Thermomechanical Processing. Milano, Italia, Associazione Italiana di Metallurgia, 5050.

Somani, M. C., Porter, D. A., Karjalainen, P., Misra, D. K. (2014) On Various Aspects of Decomposition of Austenite in a High-Silicon Steel During Quenching and Partitioning. Metall. Mater. Trans. A, 45A (2014) 1247–57.

Somani, M.C.; Porter, D.A.; Karjalainen, L.P.; Suikkanen, P.P.; Misra, R.D.K. (2015). Process design for tough ductile martensitic steels through direct quenching and partitioning. – Materials Today: Proceedings 2, S631–S634.

Somani, M.C.; Pyykkönen, J.M.; Porter, D.A.; Karjalainen, L.P.; Kömi, J.I. (2015). Influence of composition and prior deformation on phase transformation temperatures and hardness in direct quenching using physical simulation. – Materials performance and characterization 4 (3), 341–364.

Somani, Mahesh Chandra; Porter, David Arthur; Hamada, Atef S.; Karjalainen Leo Pentti (2015). High-Temperature Flow Stress and Recrystallization Characteristics of Al-Bearing Microalloyed TWIP Steels. – Metallurgical and Materials Transactions A 46 (11), 5329–5342.

Somani, Mahesh; Hannula, Jaakko; Kaijalainen, Antti; Misra, Devesh; Porter, David; (2017). An Appraisal of Direct Quenching for the Development and Processing of Novel Super-High Strength Steels. – Materials Science Forum 879, 1819–1827.

Tervo, Henri; Kaijalainen, Antti; Porter, David; Pikkarainen, Teppo; Kesti, Vili; Mehtonen, Saara; Leinonen, Mervi (2015). Effect of Impurity Level on the Mechanical Properties of Ultra-High-Strength Steel. Proceedings of the 9th International Conference on Clean Steel. Budapest, Hungarian Mining and Metallurgical Society. 1–11.

Urbanec, Julia; Saastamoinen, Ari; Kivivuori, Seppo; Louhenkilpi, Seppo (2015). Fast Salt Bath Heat Treatment for a Bainitic/Martensitic Low-Carbon Low-Alloyed Steel. – Metallurgical and Materials Transactions A 46A (11), 5343–5349.

Vuorinen, Esa; Heino, Vuokko; Ojala, Niko; Haiko, Oskari; Hedayati, Ali (2016). The effects of microstructure on erosive-abrasive wear behavior of carbide free bainitic and boron steels. The 17th Nordic Symposium on Tribology – NORDTRIB 2016. 15–19.

Wallin, Kim; Karjalainen-Roikonen, Päivi; Pallaspuro, Sakari (2015). Estimating low temperature fracture properties for very high strength steels. The Twenty-fifth International Offshore and Polar Engineering Conference, 21–26 June, Kona, Hawaii, USA. Proceedings of the International Offshore and Polar Engineering Conference. 301–308.

Wallin, Kim; Karjalainen-Roikonen, Päivi; Pallaspuro, Sakari (2016). Low-Temperature Fracture Toughness Estimates for Very High Strength Steels. – International journal of offshore and polar engineering 26 (4), 333–338.

Wallin, Kim; Pallaspuro, Sakari; Karjalainen-Roikonen, Päivi; Suikkanen, Pasi (2015). Applicability of the Master Curve Method to Ultra High Strength Steels. ASME 2015 Pressure Vessels and Piping Conference : Volume 1B : Codes and Standards. July 19–23, 2015, Boston, Massachusetts, USA. New York, PVP2015-45554.

Wallin, Kim; Pallaspuro, Sakari; Valkonen, Ilkka; Karjalainen-Roikonen, Päivi; Suikkanen, Pasi (2015). Fracture properties of high performance steels and their welds. – Engineering fracture mechanics 135, 219–231.

BSA P3 SP3: Novel Sustainable Stainless Steels (NovSuSS)

Anttila S., Heikkinen H-P., Säynäjäkangas J., Porter, D. 2015. Impact energy and fracture appearance in welds of some ferritic stainless steels. 8th European Stainless Steel Conference.

Anttila, S., Lauhikari, V., Heikkinen, H-P. Porter, D. 2016. Slag island characteristics and weld penetration in very low sulphur 18 % Cr stabilized ferritic stainless steel. Welding in the World 60, 485–496.

Anttila S., Aula M., Porter D. 2017. Behaviour and influence of slag islands in ferritic stainless steel welds. Manuscript in preparation.

Juuti T., Uusikallio S., Kaijalainen A., Heinonen E-, Tun Tun N. and Porter D. 2016. The effect of sample preparation on the microstructure of austenitic-ferritic stainless steel, Materials Science Forum 879, 873–878.

Juuti T., Rovatti L, Kömi J., Porter D. 2017. Break Down of Variables Controlling Ambient and High Temperature Yield Strength of Ferritic Stainless Steel Susceptible to Intermetallic Phase Formation. Manuscript in Preparation.

Kodukula S., Ylimäinen T., Kela J., Anttila S. 2017. Development of new high-performance cost-efficient high-Cr stainless steel grade for sheet forming applications. Manuscript in preparation.

Manninen, T., Vierelä, R., Ylitolva, M., Leinonen, O. Ilmola J., Larkiola, J. 2017. A Comparative Study of Two Different Methods for Determination of Forming Limits in the First Quadrant. Proceedings of 9th European Stainless Steel and Duplex Stainless Steel Conference. May 25–27, 2017, Bergamo, Italy.

Miettunen I., Anttila S., Kaupinmäki T., Porter D. 2016, The effect on Ni, Mn and tempering on austenite reversion in 13% Cr martensitic stainless steel, 5th International Conference on Thermomechanical Processing 2016, 26–28 October, 2016, Milan, Italy.

Miettunen I., Kaupinmäki T., Anttila S., Porter D. 2017. Improved ductility via two-step heat treatment in low-C and low-Ni martensitic stainless steel. Proceedings of 9th European Stainless Steel Conference, 25–27 May, 2017, Bergamo, Italy.

Nevasmaa, P., Karjalainen-Roikonen, P. 201, Low-temperature fracture characteristics of new 11% Cr and 18–21% Cr ferritic stainless steel grades for welded structures. IIW-Doc. IX-2562-16. Proc. Conf. "69th IIW Annual Assembly and International Conference", Melbourne, 10–15 July 2016. Australia: The International Institute of Welding (IIW), 22. Bergamo, Italy.

Nevasmaa, P., Karjalainen-Roikonen, P. 2017. Fracture mechanical analysis of low-temperature fracture characteristics of large-scale U-beam 3-point bend tests on new ferritic stainless steel grades for welded structures. Proceedings of 9th European Stainless Steel Conference, 25–27 May, 2017.

Palosaari, M., Juuti, T.,Manninen, T. 2015. The effect of post-annealing cooling rate on the yielding behavior of type EN 1.4016 ferritic stainless steel. In: Proceedings of 8th European Stainless Steel and Duplex Stainless Steel Conference. Graz, Austria. April 28–30, 2015.

Papula, S., Anttila, S., Sarikka, T., Talonen, J., Virkkunen, I., Hänninen, H. 2016, Strain hardening of cold-rolled lean-alloyed metastable ferritic-austenitic stainless steels, Materials Science and Engineering A, 677 11–19.

Papula S., Talonen J., Heikkinen H-P., Sarikka T., Hänninen, H. 2017. Martensitic transformation and delayed cracking in ferritic-austenitic stainless steels, Global Young Scientists Summit 2017, Jan 15–20, Singapore.

Papula S. 2017. Hydrogen embrittlement in metastable lean-alloyed ferritic-austenitic stainless steels. Manuscript in preparation.

Uusikallio S., Miettunen I., Anttila S., Manninen T., Nevasmaa P. 2017. Suitability of size adjustment in impact toughness transition region for subsized ferritic stainless steel Charpy-V results, Proceedings of 9th European Stainless Steel Conference, 25–27 May, 2017, Bergamo, Italy.

BSA P4: Fundamentals and Modeling

Auerkari, P., Yli-Olli, S., Penttilä, S., Tuurna, S., Pohja, R. 2015. Performance of high temperature materials for efficient power plant: the water side challenge – accepted manuscript. ASME.

Arola A.-M., Kaijalainen A., Kesti V., Evaluation of bendability of hot-rolled S960 grade steel using optical strain measurements and FE-modelling, Key Engineering Materials Vols. 651-653 (2015), pp. 610–616.

Arola A.-M., Kaijalainen A., Kesti V., The Effect of Surface Layer Properties on Bendability of Ultra-High Strength Steel, AIP Conf. Proc. 1769, (2016), 200024.

Arola A-M., Kesti V., Ruoppa R., The Effect of Punch Radius on the Deformation of Ultra-High Strength Steel in Bending, Key Engineering Materials, Vol. 639(2015), 139–146.

Björk T, Tuominen N, Lähde T, Effect of the secondary bending moment on K-joint capacity, ISTS15 conference, Rio de Janeiro (2015).

Carpén L., Rajala P., Bomberg M. 2015. Microbially Induced Corrosion in Deep Bedrock. Advanced Materials Research. Trans Tech Publications Ltd, vol. 1130 pp. 75–78.

Dabiri M., Isakov M., Skriko T., Björk T. "Experimental fatigue characterization and elasto-plastic finite element analysis of notched specimens made of direct-quenched ultra-high strength steels". Proc IMechE Part C: Journal of Mechanical Engineering Science.

Dabiri M., Laukkanen A., Björk T. Fatigue microcrack nucleation modeling: An Overview. International Review of Mechanical Engineering.

Dabiri M., Skriko T., Björk T. Preparation of specimens for fatigue testing; effect of machining and post-treatments on surface residual stress. International Journal of Advancements in Mechanical and Aeronautical Engineering.

Dabiri M., Skriko T., Amraei M., Björk T. "Effect of side grooves on plane stress fracture behavior of compact tension specimens made of ultra-high strength steel". Key Engineering Materials, Vol 713.

Dabiri M., Björk T. "Fatigue analysis of notched specimens made of direct-quenched ultra-high strength steel under constant amplitude loading".

Dabiri M., Ghafouri M., Rohani Raftar H.R., Björk T. "Neural network-based assessment of stress concentration factors in non-load carrying T-fillet welds and its optimization using genetic algorithm". Journal of Constructional Steel Research, Vol. 128.

Heino V, Valtonen K, Kuokkala, V-T, Effect of quartzite and granite in wear surfaces on dry sliding, Tribology - Materials, Surfaces and Interfaces, Volume 8, Issue 3 (2014).

Heino V, Valtonen K, Kuokkala V-T, Sliding Wear of Quartzite and Granite Surfaces, Proceedings of Nordtrib 2014, 16th Nordic Symposium on Tribology, Århus, Denmark (2014).

Heino, V., Valtonen, K., Kivikytö-Reponen, P., Siitonen, P & Kuokkala, V.-T., Characterization of the effects of embedded quartz layer on wear rates in abrasive wear, Wear 308(1–2):174–179 (2013).

Huttunen-Saarivirta E., Rajala P., Carpén L. 2016. Corrosion behaviour of copper under biotic and abiotic conditions in anoxic ground water: electrochemical study. Electrochimica Acta 2016, 203: 350–365.

Huttunen-Saarivirta E., Rajala P., Bomberg M., Carpén L. 2017. Corrosion of copper in oxygen-deficient groundwater with and without deep bedrock micro-organisms: characterisation of microbial communities and surface processes, Applied Surface Science, 396: 1044–1057.

Jokiaho T, Saarinen T, Santa-aho S, Peura P, Vippola M, The Characterization of Flame Cut Heavy Steel – The Residual Stress Profiling of Heat Affected Surface Layer, Key Engineering Materials Vol. 674(2016), pp. 103–108.

Juuti T., Uusikallio S., Kaijalainen A., Anttila S., Hienonen E., Nyo T. and Porter D.A., The Effect of Sample Preparation on the Microstructure of Duplex Stainless Steels, Materials Science Forum Vol. 879 (2016), pp. 873–878.

Järvinen H., Järn S., Lepikko E., Järvenpää M., Peura P. ZnFe Coated 22MnB5 Steels in Direct Press Hardening: the Relationships between Coating Structure and Process Parameters, Key Engineering Materials, Vol. 674, 2016, pp. 331–336.

Järvinen H, Isakov M, Nyyssönen T, Järvenpää M, Peura P, The effect of initial microstructure on the final properties of press hardened 22MnB5 steels, Materials Science and Engineering: A, Vol. 676, 2016, pp. 109–120.

Kaijalainen A., Karjalainen P., Porter D., Suikkanen L.P., Kömi J., Kesti V. & Saarinen T., Effect of Inclusions on the Properties of Ultra-high-strength Low-alloy Steel with a Martensitic-bainitic Microstructure, Proc. 8th Int. Conf. Clean Steel, Budapest, Hungary, May 14–16 (2012).

Kaijalainen A., Suikkanen P., Karjalainen L.P., Porter D., Kömi J., Limnell T., Effect of Austenite Grain Structure on the Strength and Toughness of Direct-Quenched Martensite, Journal of Alloys and Compounds (2013), pp. S642–S648.

Kaijalainen A., Suikkanen P., Karjalainen L.P., Jonas J.J., Effect of Austenite Pancaking on the Microstructure, Texture, and Bendability of an Ultrahigh-Strength Strip Steel, Metallurgical and Materials Transactions A: Vol 45, (2014), pp. 1273–1283.

Kaijalainen A., Suikkanen P., Karjalainen L.P., Porter D., Influence of Subsurface Microstructure on the Bendability of an Ultrahigh-Strength Strip Steel. Materials Science and Engineering A: Volume 654 (2016), pp. 151–160.

Kaijalainen A., Liimatainen M., Kesti V., Heikkala J., Liimatainen T., Porter D., Influence of Composition and Hot Rolling on the Subsurface Microstructure and Bendability of Ultrahigh-Strength Strip, Metallurgical and Materials Transaction A: Volume 47 (8) (2016), pp. 4175–4188.

Kaijalainen A., Suikkanen P., Porter D., Effect of re-austenitization on the transformation texture inheritance, IOP Conf. Series: Materials Science and Engineering 82 (2015), 012058.

Kaijalainen A., Pallaspuro S., Porter D., Tempering of Direct Quenched Low-Alloy Ultra-High-Strength Steel, Part I – Microstructure, Advanced Materials Research Vol. 922 (2014), pp. 316–321.

Kaijalainen A., Liimatainen M., Kesti V., Anttila S., Suikkanen P., Porter D., Effect of Red Scale on the Bendability of Ultra-High-Strength Strip Steel, Materials Science Forum Vol. 879 (2016), pp. 879–884.

Kaijalainen A., Kesti V., Arola A.-M., Liimatainen M., Porter D.A., Microstructural Investigation of Strain Localization, Void Formation and Fracture Mechanisms in Ultrahigh-Strength Steel Bending, Advancements in Theoretical and Applied Plasticity, (Proc. Of Plasticity'16), Kona, Hawaii, USA, pp. 40–42.

Kaijalainen A., Liimatainen M., Kesti V., Liimatainen T., Porter D.A., Influence of Composition and Hot-Rolling on the Subsurface Microstructure and Bendability of Ultrahigh-Strength Strip, Advancements in Theoretical and Applied Plasticity, (Proc. Of Plasticity'16), Kona, Hawaii, USA, pp. 37–39.

Kaijalainen, A. Effect of microstructure on the mechanical properties and bendability of direct-quenched ultrahigh-strength steels, Acta Univ. Oul. C 582, 2016, 116 pp.

Kaijalainen A., Vähäkuopus N., Somani M., Mehtonen S., Porter D., Kömi J., The Effects of Finish Rolling Temperature and Niobium Microalloying on the Microstructure and Properties of a Direct Quenched High-Strength Steel, Archives of Metallurgy and Materials, Vol. 62, (1) (2017).

Kesti V., Kaijalainen A., Väisänen A., Järvenpää A., Määttä A., Arola A-M., Mäntyjärvi K., Ruoppa R., Bendability and Microstructure of Direct Quenched Optim® 960QC, Materials Science Forum Vols. 783–786 (2014), pp. 818–824.

Kesti V., Kaijalainen A., Mourujärvi J., Ruoppa R., Bendability and Microstructure of Optim® 700 MC Plus, Nordic Steel Construction Conference 2015, Tampere.

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 Coatings, 25(2016), pp. 1127–1137.

Kinnunen P., Bomberg M., Rajala P., Carpén L. 2015. Industrial Views to Microbe-Metal Interactions in Sub-Arctic Conditions. Advanced Materials Research. Trans Tech Publications Ltd, vol. 1130 pp. 114–117.

Lehto P., Remes H., Romanoff J., Sarikka T. Characterisation of the local grain size variation of welded structural steel. Welding in the World 60 (2016), Issue 4, 673–688.

Lehto P, Remes H, Saukkonen T, Hänninen H, Romanoff J. Influence of grain size distribution on the Hall-Petch relationship of welded structural steel, Materials Science and Engineering: A 592 (2014) 28–39.

Lehto P, Remes H, Romanoff J, Sarikka T. Characterisation of the local grain size variation of welded structural steel. The 68th IIW Annual Assembly and International Conference, Helsinki, Finland, June 28 – July 3, 2015. IIW Doc.No IX-2516-15 (IX-L-1137-15).

Liinalampi, S., Remes, H., Lehto, P., Lillemäe, I., Romanoff, J., Porter, D. 2016. Fatigue strength analysis of laser-hybrid welds in thin plate considering weld geometry in microscale. International Journal of Fatigue 87 (2016) pp. 143–152.

Lindroos, M. (2016). Experimental and Numerical Studies on the Abrasive and Impact Behavior of Wear Resistant Steels. Publication; Vol. 1416, Tampere University of Technology.

Lindroos, M., Apostol, M., Ratia, V., Valtonen, K., Laukkanen, A., Molnar, W., Holmberg, K., Kuokkala, V-T. The effect of impact conditions on the wear and deformation behavior of wear resistant steels, Wear 328–329(2015), 197–205.

Lindroos M., Apostol, M., Heino, V., Valtonen, K., Laukkanen, A., Holmberg, K., Kuokkala, V-T. The deformation, strain hardening, and wear behavior of chromium-alloyed hadfield steel in abrasive and impact conditions, Tribology Letters 57(2015)23, 1–11.

Lindroos, M., Apostol, M., Kuokkala, V-T., Laukkanen, A., Valtonen, K., Holmberg, K., Oja, O. Experimental study on the behavior of wear resistant steels under high velocity single particle impacts, International Journal of Impact Engineering 78(2015), 114–127.

Lindroos, M., Valtonen, K., Kemppainen, A., Laukkanen, A., Holmberg, K., Kuokkala, V-T. Wear behavior and work hardening of high strength steels in high stress abrasion, 323–333(2015), 32–40.

Lindroos, M., Kuokkala, V-T., Lehtovaara, A., Kivikyto-Reponen, P. Effects of Strain and Strain Rate on the Abrasive Wear Behavior of High Manganese Austenitic Steel, Key Engineering Materials, 527(2013), 211–216.

Mardoukhi A., Mardoukhi Y., Hokka M., V.-T Kuokkala. Effects of strain rate and surface cracks on the mechanical behaviour of Balmoral Red granite. Philosophical Transactions of Royal Society A. Vol. 375 (2085): 20160179.

Mardoukhi A., Mardoukhi Y., Hokka M., V.-T Kuokkala. Effects of heat shock on the dynamic tensile behavior of granitic rocks. Rock mechanics and rock engineering.

Mehtonen S., Kesti V., Mourujärvi J., Kaijalainen A., Effect of Thermomechanical Processing on the Microstructure, Texture and Impact Toughness of Two 700 MPa Strength Class Structural Steels, Proc. 5th Int.Conf. Thermomechanical Processing, Milan, Italy, 26.– 28. October 2016.

Miettunen I., Anttila S., Kaupinmäki T., Porter D. The effect on Ni, Mn and tempering on austenite reversion in 13% Cr martensitic stainless steel, 5th International Conference on Thermomechanical Processing 2016, 26–28 October, 2016, Milan, Italy.

Ojala, N., Valtonen, K., Heino, V., Kallio, M. Aaltonen, J. Siitonen, P., & Kuokkala, V.-T., Effects of composition and microstructure on the abrasive wear performance of quenched wear resistant steels, Wear 317(1–2):225–232(2014).

Ojala N., Valtonen K., Kivikytö-Reponen P., Vuorinen P., Siitonen P., and Kuokkala V.-T., Effect of test parameters on large particle high speed slurry erosion testing, Tribol. – Mater. Surfaces Interfaces, vol. 8, no. 2, pp. 98–104, Jun. 2014.

Ojala N., Valtonen K., Kivikytö-Reponen P., Vuorinen P., and Kuokkala V.-T., High speed slurry-pot erosion wear testing with large abrasive particles, Finnish J. Tribol., 2015.

Ojala N., Valtonen K., Antikainen A., Kemppainen A., Minkkinen J., Oja O., and Kuokkala V.-T., Wear performance of quenched wear resistant steels in abrasive slurry erosion, Wear 354–355(2016)21–31.

Ojala N., Valtonen K., Minkkinen J. and Kuokkala V.-T., Edge effect in high speed slurry erosion wear tests of steels and elastomers, The 17th Nordic Symposium on Tribology – NORDTRIB 2016, June 2016, Finland.

Pallaspuro S., Limnell T., Suikkanen P., Porter D. T0– T28J correlation of Low-carbon Ultra-high-strength Quenched Steels. Procedia Materials Science 3 (2014) 1032–1037.

Pallaspuro S., Kaijalainen A., Limnell T., Porter D., Tempering of Direct Quenched Low-Alloy Ultra-High-Strength Steel, Part II – Mechanical Properties, Advanced Materials Research Vol. 922 (2014), pp. 580–585.

Pallaspuro S., Yu H., Kisko A., Porter D & Zhang Z. Fracture toughness of hydrogen charged as-quenched ultra-high-strength steels at low temperatures.

Pohjonen A., Kaijalainen A., Somani M., Larkiola J., Analysis of Bainite Onset During Cooling Following Prior Deformation at Different Temperatures, KomPlastTech 2017.

Rajala P., Carpén L., Vepsäläinen M., Raulio M., Huttunen-Saarivirta E., Bomberg M. 2016. Influence of carbon sources and concrete on microbially induced corrosion of carbon steel in subterranean groundwater environment, CORROSION ;72(12):1565–1579.

Rajala P., Bomberg M., Huttunen-Saarivirta E., Priha O., Tausa M., Carpén L. 2016. Influence of Chlorination and Choice of Materials on Fouling in Cooling Water System under Brackish Seawater Conditions. Materials. 2016; 9(6):475.

Rajala P., Vepsäläinen M., Bomberg M., Carpén L. Microbial fouling and corrosion of carbon steel in deep anoxic alkaline groundwater. In press, Biofouling.

Rajala P., Sohlberg E., Priha O., Tsitko I., Väisänen H., Tausa M., Carpén L. Biofouling on Coated Carbon Steel in Cooling Water Cycles Using Brackish Seawater. J. Mar. Sci. Eng. 2016, 4, 74.

Rajala P., Carpén L., Vepsäläinen M., Raulio M., Sohlberg E., Bomberg M. 2015. Microbially induced corrosion of carbon steel in deep groundwater environment. Frontiers in Microbiology 6:647.

Rajala P., Bomberg M., Kietäväinen R., Kukkonen I., Ahonen L., Nyyssönen M., Itävaara M. 2015. Rapid Reactivation of Deep Subsurface Microbes in the Presence of C-1 Compounds. Microorganisms. 3(1):17–33.

Rajala P., Raunio M., Sohlberg E., Priha O., Carpén L. 2015. The effect of chlorination on microbially induced corrosion of carbon steel in cooling water system under brackish seawater conditions. Nordic Corrosion Congress – 18. May 20–22, Stavanger, Norway.

Ratia, V., Valtonen, K., Kemppainen, A. & Kuokkala, V.-T., Impact-abrasion wear testing of wear resistant steels, Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology, 227(8):868–877(2013).

Ratia, V., Valtonen, K., Kemppainen, A., Vippola, M. & Kuokkala, V.-T., High-Stress Abrasion and Impact-Abrasion Testing of Wear Resistant Steels, Tribology Online 8(2):152–161(2013).

Ratia, V., Heino, V., Valtonen, K., Kemppainen, A., Siitonen, P., Vippola, M. & Kuokkala, V.-T., Effect of abrasive properties on the high-stress three-body abrasion of steels and hard metals, Finnish Journal for Tribology, 32(1):3–18(2014).

Ratia, V., et al. "Impact behavior of martensitic steel at low temperatures", Proceedings of Nordtrib 2016, 9 p.

Raunio M., Rajala P., Priha O., Huttunen-Saarivirta E., Carpén L. 2016. Corrosion and biofouling on stainless steels in Baltic Sea water environment: a cooling water pilot study. In: Baltica X. International Conference on Life Management and Maintenance for Power Plants.

Saastamoinen A., Kaijalainen A., Porter D., Suikkanen P., Effect of Titanium and Nitrogen Content on the Microstructure, Hardenability and Mechanical Properties of Direct Quenched and Tempered Ultra-High Strength Structural Steel, Proc. 5th Int.Conf. Thermomechanical Processing, Milan, Italy, 26.–28. October 2016.

Somani M., Hannula J., Kaijalainen A., Misra D., Porter D., An Appraisal of Direct Quenching for the Development and Processing of Novel Super-High Strength Steels, Materials Science Forum Vol. 879 (2016), pp. 1819–1827.

Tervo H., Kaijalainen A., Porter D., Pikkarainen T., Kesti V., Mehtonen S., Leinonen M., Effect of Impurity Level on the Mechanical Properties of an Ultra-High-Strength Steel, Proc. 9th Int. Conf. Clean Steel, Budapest, Hungary, 8–10. September 2015.

Tuurna, S., Yli-Olli S., Penttilä, S., Auerkari, P., Huang, X. 2015. Supercritical oxidation of boiler tube materials. Journal of Nuclear Engineering and Radiation Science – accepted manuscript. ASME.

Terva J., Valtonen K, Siitonen P., Kuokkala V.-T., Correlation of wear and work in dual pivoted jaw crusher tests, Proceedings of Nordtrib 2016, 17th Nordic Symposium on Tribology, Hämeenlinna, Finland (2016).

Tuominen N., Björk T., Litmanen J. Sekundäärisen momentin vaikutus hitsin lujuuteen, Rakenteiden mekaniikka, Vol. 48, 2016.

Valtonen, K, et al. 2016. Comparison of laboratory wear test results with the in-service performance of cutting edges of loader buckets, Proceedings of Nordtrib 2016, 12 p., submitted to Wear.

Vuorinen E., Ojala N., Heino V., Rau C., and Gahm C., Erosive and abrasive wear performance of carbide free bainitic steels – comparison of field and laboratory experiments, Tribology international, vol. 98, pp. 108–115, 2016.

Wallin K, Pallaspuro S, Valkonen I, Karjalainen-Roikonen P, Suikkanen P. Fracture properties of high performance steels and their welds, Engineering Fracture Mechanics 135 (2015) 219–231.

Wallin K., Karjalainen-Roikonen P., Pallaspuro S., Estimating Low Temperature Fracture Properties for Very High Strength Steels, Proceedings of the Twenty-fifth (2015) International Ocean and Polar Engineering Conference, ISOPE-I-15-428.

Wallin K., Pallaspuro S., Karjalainen-Roikonen P., Suikkanen P.. Applicability of the Master Curve Method to Ultra High Strength Steels, ASME 2015 Pressure Vessels and Piping Conference Paper No. PVP2015-45554, pp. V01BT01A027; 16 pages.

Wallin K., Karjalainen-Roikonen P., Pallaspuro S. Low-Temperature Fracture Toughness Estimates for Very High Strength Steels. International Journal of Offshore and Polar Engineering 26 (04), 333–338.

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