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FINAL REPORT 4/2014

FIMECC
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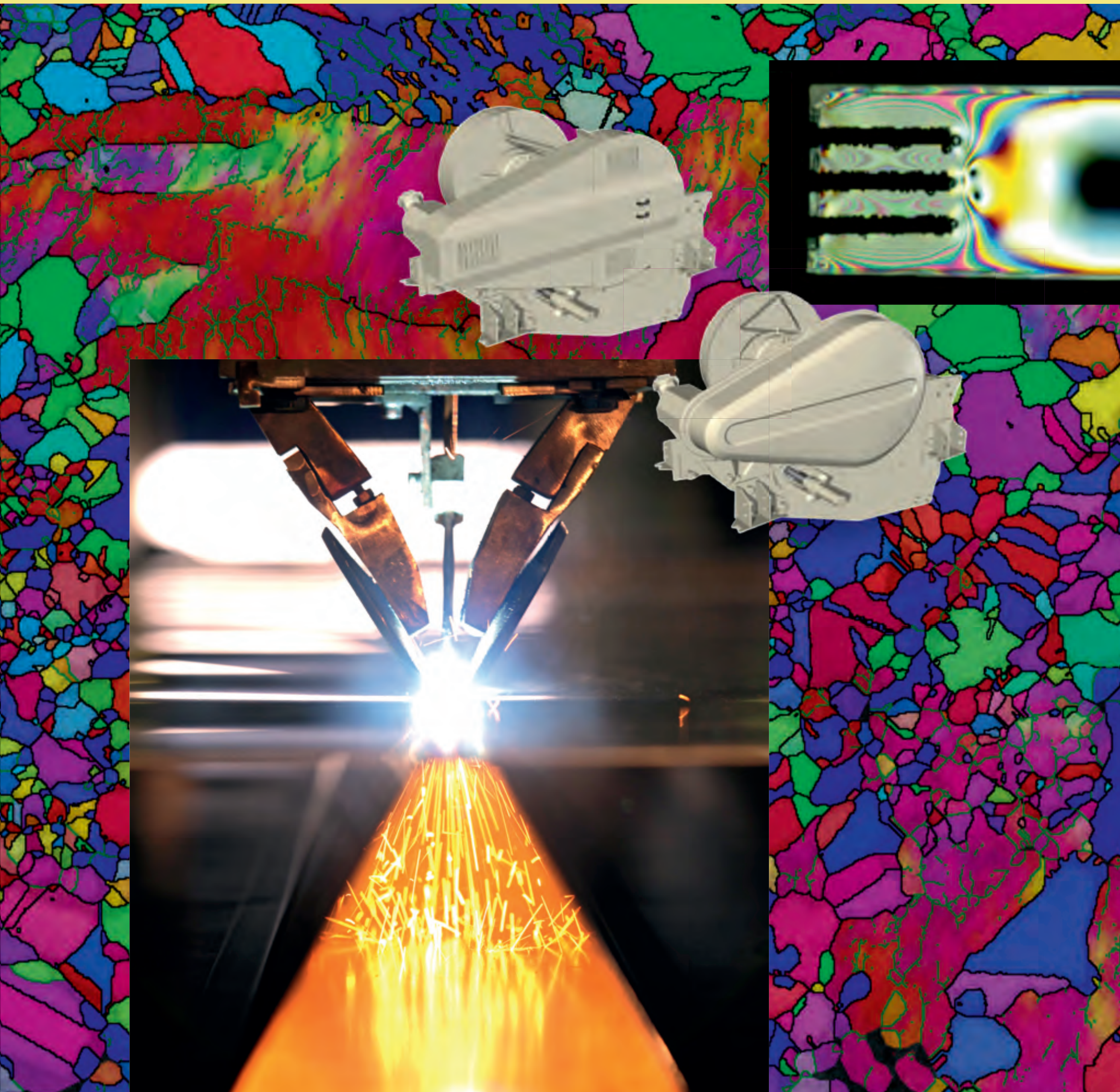
Light and Efficient Solutions – LIGHT

2009-2014



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PREFACE

LIGHT – Launch of FIMECC Materials Research

The first Strategic Research Agenda of FIMECC defined the following research domains for the Breakthrough Materials theme:

- Light constructions
- Cutting, forming, joining and surface treatments
- Active and functional solutions
- Demanding applications
- Production technology.

When preparing the research programmes, it was soon discovered that production and manufacturing technologies were inseparable from material and application research. With these aspects needing to be integrated, preparation of three programmes was initiated:

- Light and Efficient Solutions (LIGHT)
- Demanding Applications (DEMAPP)
- Active and Functional Solutions (ActiFun)

Programme plans for FIMECC LIGHT, closely followed by FIMECC DEMAPP, were completed during the first half of 2009. Insufficient volume was obtained for ActiFun, although several separate research projects were launched on the basis of the preparation work.

The vision of the FIMECC LIGHT programme was: To enable Finnish industries to gain a leading international position in the development of a future generation of advanced materials, structures, and systems which will have reduced weight, increased performance, improved energy efficiency and a reduced environmental footprint. Although the need for ever-lighter structures is obvious today, this was not apparent seven years ago when preparation work began. In this respect, the decision to execute a separate interdisciplinary programme specifically around this theme was quite visionary.

Eleven companies and four universities have joined as partners in FIMECC LIGHT, with a total volume of EUR 21 million. Many other companies have also participated by making prototypes and acting in case studies when testing novel material concepts. FIMECC LIGHT was unique in that it combined all disciplines related to creating a new lighter product: material research, design rules, manufacturing technologies and environmental impacts. Strong emphasis was laid on research into application requirements, and this was used as input data for the other research subjects. A separate project was dedicated to low-density materials, which opened an easy access to the programme for several SMEs using these materials.

The programme has produced a large number of publications: 37 research reports, 61 conference papers and journal articles, 9 doctoral theses (4 completed and 5 in their final stage) and 10 patents. As one of the first programmes, FIMECC LIGHT has created much of the procedures used in the preparation and governance of other FIMECC research programmes. It has also been a cornerstone for the new Breakthrough Materials theme programmes: Breakthrough Steels and Applications BSA and Hybrid Materials HYBRIDS.

I want to thank Tekes for their confidence in the FIMECC LIGHT programme and their financial support, the programme manager, the FIMECC staff and, above all, those persons who have participated in the execution of the research work and helped to create this excellent programme.

Arto Ranta-Eskola
Chairman

FIMECC Breakthrough Materials
Steering Group

Lightening the Future

The FIMECC LIGHT programme has been a challenging project due to the different concepts and views from a wide range of participants, ranging from metallurgists to experts in life-cycle analysis and fibre-reinforced plastics. This varied group of people, and their occasionally conflicting interests, have nevertheless achieved unity under a common goal: to create a programme – in co-operation not just with industry but with different research institutes in Finland – in which world-class research produces novel solutions for lighter and more efficient industrial applications in machine engineering.

While the programme results are expressed mainly in scientific articles and in theses written from the results of the research, a number of patents and products have also been issued during the programme period. The main highlights are covered briefly in this report.

When reviewing the experiences of these years, the significance of long-term funding cannot be overly emphasised. Such funding enables full concentration on research without the disturbance to day-to-day work of continual funding applications, something appreciated by every partner in the field. We are all grateful for Tekes's funding policy for enabling the improvement in industrial-driven research in Finland through these long-term FIMECC programmes.

As in all aspects of life, the programme had its ups and downs. Nothing is linear in Nature, nor is it in this kind of large project work, with its many bumps, turns, decelerations and accelerations. Still, it is surprising how closely the plans and projections defined in the preparation work and expressed in the project plan were executed.

The ground covered in these five short years could really have us talking in terms of light years, but not so expansively, perhaps, if we describe the burden this placed on the programme manager. Though principally serving as important networking venues in augmenting team work, this programme manager had a thoroughly enjoyable time in the project meetings and workshops, as well as the annual seminars. One of the project leaders suggested that excellent research derives from professionalism combined with a mischievous sense of humour. 'Being professional and having fun' could well be the motto for the team work shown in the FIMECC LIGHT programme.

For the programme manager, then, the various meetings have given great delight and satisfaction in seeing and hearing the enthusiasm and professionalism shown when results are presented to the teams, especially by the younger researchers.

The close co-operation in research between industry and the universities has intensified and expanded remarkably during these programme years, and there is no doubt in my mind that this trend will continue.

I thank all participants of the programme. Keep up the good work!

Tapani Halme
Programme Manager

FIMECC LIGHT

FIMECC Pioneers Create a Platform for Implementing the 4th Industrial Revolution

During the days when we started FIMECC's first two research programmes, Innovation and Networks (I&N) and LIGHT, in the spring of 2009, we were a start-up company having just a vision of what a co-creation and innovation platform could be. We had a solid basis in the strategic research agenda created by Finnish manufacturing, mechanical engineering, marine, and metals industries. We had a good research plan, oriented towards public-private partnership, written by a small and determined FIMECC LIGHT consortium. On the down side, we had no tested leadership, decision-making, or management practices. FIMECC LIGHT was a pioneering programme in creating the management systems and practices we have today. Everybody – companies, universities, research institutions, Tekes, and FIMECC shareholders – believed that we would get more out of research and development by joining forces and pooling competence. A thank you to all who believed in us and invested in FIMECC!

After six years of operations we have reached a significant position in European manufacturing R&D&I decision-making, with our track record in creating results noted positively throughout the continent. Five years of FIMECC LIGHT has brought the consortium far along the academic path and created many new technology openings and applications. Some of these are already in the market.

Feedback shows that LIGHT participants have reached almost all the goals they set in 2009. In some cases, such as in the strength of steel grades, the performance achieved ranks as highest in the EU! The consortium's compactness and high level of commitment has enabled us to overcome many managerial challenges in the new open innovation system, which lacked precise guidelines when we started. I am extremely delighted we were able to achieve flexible integration into LIGHT of non-metal material research and participants. This had the effect of making the programme more versatile and cross-disciplinary. FIMECC LIGHT has shown the way towards broad and excellent materials research in FIMECC. This development reveals itself as the increase of materials research in the FIMECC portfolio, and in the form of the largest industrial doctoral school in Finland, Breakthrough Materials Doctoral School, which is linked to our new HYBRIDS and BSA programmes.

The key global discussion in manufacturing in 2013 was the 4th Industrial Revolution. In Germany, this is called "Industrie 4.0", meaning total digitalisation and internet connectedness in products, services, and processes. This revolution is the first-ever in technology to be announced in advance. FIMECC is implementing this revolution through a wide variety of activities. Our strong presence in Germany through the FIMECC Factory in Aachen, and strategic partnerships with German research and industry networks, help our programme participants to identify new opportunities with the world's technology leaders.

Spend enjoyable moments reading the highlights of the excellent results shown in this book!

Harri Kulmala
CEO

FIMECC Ltd

Larger than the Sum of the Participants

In considering interaction and co-operation with universities as an integral part of research and development in industrial enterprises, the LIGHT programme, in conjunction with other FIMECC programmes, has brought small and medium-sized companies (SMEs) to the same level as the bigger industrial representatives. Of course, this was largely made possible by long-term Tekes funding through the SHOK instrument. In the LIGHT programme this was shown to be a fundamentally different concept for supporting and developing Finland's industrial basis when compared to other forms of government support.

Small and medium-sized companies have had – and will continue to have – totally different capabilities and resources and shorter result time spans compared to big industry. Being part of a larger consortium, as is the case with the LIGHT programme, has given SMEs the chance to incorporate individual research on the company level into a larger corporate and academic research agenda. This has consequently enabled the extension of research activities in SMEs from the rapid product development demanded by global competition to more basic research, and thus to longer-term industrial product development.

The natural networking that has taken place at consortium level during the programme has also given LIGHT programme SMEs the opportunity to advance their objectives and businesses along with the larger participants. This is vitally important considering the relatively small Finnish industrial base compared to the global level.

Industrially driven research, which is the basis for the SHOK concept, is especially important for SMEs, and I cannot emphasise nearly enough the significance of project steering group meetings. When functioning properly, these set targets and deadlines and evaluate results, thus creating the proper environment for goal-oriented research in which participants are constantly aware of what others are doing, and can position their work on a larger research field.

As expressed in the heading, the LIGHT programme has shown itself to be larger than the sum of its participants. My hope is that this SHOK concept will continue to be available to Finnish companies, and especially SMEs, far into the future.

Erkki Lappi
Managing Director

Ekin Muovi Ltd

Research Institutes Representative's Review

The Light and Efficient Solutions (LIGHT) programme brought together a wide variety of companies and universities working on materials science and engineering. The achievement of lightweight structures is a unifying theme for many branches of materials, and the LIGHT programme covered materials ranging from ultra-high-strength steels to polymer composites: materials in the forefront of development when targeting reductions in energy consumption, raw materials usage and emissions.

Researchers from Aalto University, Lappeenranta University of Technology, Tampere University of Technology and the University of Oulu have been involved in the programme in the development and application of new steels, hybrid materials and composite materials. They have also been developing dimensioning rules for the new materials to enable their efficient use in new structures, and investigating the cradle-to-grave environmental footprint of lightweight solutions.

The research questions in the FIMECC LIGHT programme have been selected to be both challenging and relevant for both academia and industry, or put another way, to be right at the forefront of the industrial, scientific and societal arenas. The high level of industrial interest for the academic work has been highly motivating for university researchers, who have also been able to see their own work in a wider, industrially important perspective. This wider perspective has been reinforced by communication and co-operation between researchers working on different aspects of a common goal at different universities, both in Finland and abroad. The industry–university and inter-university co-operation enabled by the programme also improved the quality of the research by increasing the range of experimental techniques and equipment available to individual researchers.

The new FIMECC Programme funding instrument has also given a long-term perspective and continuity to the academic research, helping universities to develop and assure research quality through the production of publications and doctoral degrees. The successful and well-established research networks built up in the LIGHT programme in fact continue to operate in the new FIMECC programmes Breakthrough Steels and Applications (BSA) and Hybrid Materials (HYBRIDS), thereby reinforcing the long-term nature of the research.

We would like sincerely to thank FIMECC and Tekes for their funding and excellent management resources that made the high-level international LIGHT research possible.

David Porter
Professor, University of Oulu

Jyrki Vuorinen
Professor, Tampere University of Technology

PROGRAMME KEY FIGURES

Programme value (EUR):	**20.700 million**
Programme duration:	**2009 – 2014**
Number of publications:	**61 submitted**
Number of Doctoral Theses:	**9**
Number of Master's Theses:	**37**
Number of patent applications/patents:	**10**

PROJECT NAME

P1 Production and Properties of Breakthrough Materials

The project focused on the development of new ultra-high-strength carbon steels and stainless steels. There is growing demand for these steels for developing lightweight structures in many application areas. Weight reduction in moving vehicles is particularly attractive, as lower weight means higher payload and lower fuel consumption, with resulting cost savings over the vehicle life cycle. Development of lightweight structures using ultra-high-strength steels is also important from the environmental viewpoint, as reduced use of material and lower fuel consumption means lower emissions. New ultra-high-strength steels are key themes in both Ruukki and Outokumpu R&D strategies.

The simultaneous optimisation of steel strength, ductility and toughness is a classic dilemma for the metallurgist. The cost of raw materials should also be kept at a minimum with, in the case of stainless steels, no compromise in corrosion resistance. Optimisation of material properties requires a thorough understanding of the microstructural features affecting the material behaviour and deformation mechanisms. Increased understanding of these features and application of the generated knowledge in the development of next generations of ultra-high-strength steels were the targets of the project.

Direct quenching is a technological innovation implemented at Ruukki two decades ago, and new families of structural steels based on direct quenching technology have been developed under the FIMECC LIGHT programme. Ruukki already had a very strong position in thin ultra-high-strength steels when the programme started, but the research then carried out has promoted Ruukki's market leadership in this area. Substantial efforts have been made to improve the mechanical properties and usability of the new steels, to help Ruukki stay ahead of its competitors. New combinations of chemical composition, bainitic or martensitic microstructure and thermomechanical processing have been established. Significant attention has also been paid to cleanliness, and to phenomena affecting the bendability of steel. Research work led to fundamental knowledge that allowed the production of direct quenched structural strip steels up to 10 mm thick with yield strengths of 900 and 960 MPa. In addition, the metallurgical research has enabled development of a totally new kind of strip steel with yield strength of 700MPa. This new steel combines excellent toughness, cut-edge quality and formability in a way that is unsurpassed on the global market.

Considerable research work together with the project partners on combining direct quenching and tempering has enabled the production of new thicker tempered plate products with yield strengths of 700 MPa and above. Grain growth between rolling passes was identified as an important factor controlling impact toughness in thick direct quenched plates. Research showed how control of chemical composition and rolling parameters could reduce grain growth, leading to significant impact toughness improvements that allow good performance even at -60 °C. In other words, direct quenching can now be used for even the most demanding applications.

The above R&D involved both laboratory and production-scale experiments. Additional solely laboratory-scale experiments, consisting of physical simulation and pilot-scale production, generated fundamental information on exciting new possibilities for obtaining ultra-high-strength steels with excellent toughness, but without the need for expensive alloying elements or processing. It has been shown that this can be achieved by controlling the distribution of austenite films in martensitic matrices using thermomechanical rolling combined with direct quenching and partitioning.

Although this work related to metallurgical phenomena has been carried out within the FIMECC LIGHT programme, it has required close co-operation with other SHOK programmes, such as FIMECC ELEMET and DEMAPP.

The main challenge in the development of the next generation of ultra-high-strength stainless steels is the concurrent optimisation of strength and ductility and minimisation of alloying costs. The research carried out within the LIGHT programme focused on fundamental studies aimed at optimisation of alloying, and at strengthening and deformation mechanisms of austenitic microstructures. Another important topic was the delayed cracking phenomenon, one of the main barriers to the development of the next generation of cost-efficient, ultra-high-strength stainless steels.

Figure 1. **Ruukki special steels used in the world's highest (112m) truck-mounted access platform produced by Bronto Skylift**

Highlights of the results include enhanced understanding of how alloying affects the stacking fault energy and deformation mechanisms, i.e. transformation-induced plasticity (TRIP) and twinning-induced plasticity (TWIP) effects. Based on this knowledge, new alloying concepts with optimised properties were developed and tested in pilot scale.

Another important research theme was development of ultra-fine-grained and nano-twinned austenitic microstructures providing superior properties compared to conventional austenitic steels strengthened by temper rolling. One example of key findings is the definition of the optimum austenite stability with regard to fine-grained austenitic microstructure and its mechanical behaviour. Another key finding concerned how to improve the ease with which fine-grained steel can be processed by alloying of carbide- and nitride-forming elements, which efficiently restricts the grain growth.

Delayed cracking is one of the main barriers preventing the wider utilisation of low-nickel manganese-alloyed austenitic high-strength stainless steels. A substantial improvement was achieved in the understanding of the mechanisms and kinetics of delayed cracking, including clarification of the roles of hydrogen, residual stresses, martensite content and chemical composition of the steel. Design guidelines for avoiding the cracking phenomenon were developed and coupled with finite-element-forming simulations.

The knowledge generated during the project also serves as a platform on which new generations of ultra-high-strength stainless steels will be developed.

Figure 2. **Railroad cars are a typical application area for high-strength austenitic stainless steels**

Industrial relevance

"Despite the fact that Ruukki and Outokumpu operate in different business fields with different products, the fundamental metallurgical phenomena are the same, and it thus creates clear added value to carry out the metallurgical research together. The FIMECC LIGHT programme proved to be an excellent research platform for both companies," says **Juho Talonen** from Outokumpu.

Industrial relevance

"The research groups at universities need to be large enough to produce and develop new knowledge. Now researchers can discuss the same metallurgical phenomena independently of whether they are working on stainless or carbon steels. This is a huge benefit for all partners, and we also need to maintain this close co-operation in the future," adds **Jarkko Vimpari** from Ruukki.

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PROJECT NAME

P1 Production and Properties of Breakthrough Materials

CONTACT PERSON	PARTICIPANTS (ORGANISATIONS)	PROJECT DURATION	PROJECT VALUE (EUR)
JUHO TALONEN OUTOKUMPU OYJ **DAVID PORTER** UNIVERSITY OF OULU	**OUTOKUMPU OYJ** **RUUKKI METALS OY** **UNIVERSITY OF OULU** **AALTO UNIVERSITY**	**2009 – 2014**	**6.600 MILLION**

Main targets & motivation

The main objective of the project was to build knowledge enabling the development of the next generation of ultra-high-strength low-alloy and stainless steels. This involved profound studies of fundamental metallurgical phenomena, development of material models and modelling tools, and testing and development of new steel concepts in laboratory scale and in full-scale production. New ultra-high-strength steels are required for future lightweight structures in, for instance, transport applications. Use of the next generation ultra-high-strength steels will enable weight reduction, reduced fuel consumption, increased payload, and thus lower life cycle costs and environmental impact.

Results

The FIMECC LIGHT programme proved to be an excellent research platform for the participants. Despite the fact that Ruukki and Outokumpu operate in different business fields with different products, the fundamental metallurgical phenomena are the same, and it thus created clear added value to carry out the research together.

The research on low-alloy steels focused on the application of direct quenching, which lies at the core of Ruukki's strategy for increasing the share of special steels grades in its product portfolio.

Key findings and results were as follows:

- New steels with martensitic and bainitic microstructures have been developed as a result of research into the effects of chemical composition and process parameters on the metallurgical phenomena occurring during the whole process, and how they affect the final microstructure and mechanical properties.
- The factors affecting the toughness of the steel have been revealed. This has led to new steels with better properties and given rise to new ideas for the future production of even tougher steels.
- The main factors affecting the formability of direct quenched strip steels have been identified. The research, e.g. in reference 1, showed that the best possible microstructure and property combinations can be achieved by controlling the amount of deformation below the recrystallisation stop temperature. Cut edge quality, the effect of inclusions and the geometry of work tools have been shown to be important. Weldability and other workshop properties have been evaluated, and new rules and guidelines developed.
- Empirical / statistical analysis tools have been developed to predict and model the mechanical properties of direct quenched steels.
- The tempering metallurgy of direct quenched steels has been studied, in particular the effect of heating rate and peak temperature on microstructures and properties, with a view to the employment of rapid induction tempering. By studying the effects of carbon, molybdenum and titanium, it was possible to make a 1000 MPa yield strength laboratory rolled grade with excellent property combinations.
- Basic knowledge has been developed on potential future steels with yield strengths of 1100MPa and above. The coming years will show how well these ideas can be turned into profitable business. This includes new processes, microstructures and phenomena. One such idea is based on the application of thermomechanical rolling combined with quenching and partitioning to give martensite–austenite microstructures without the need for expensive alloying elements. Figure 1 shows how the new concept compares to a fully martensitic steel with the same strength. (See also references 2 and 3).

- The understanding of the limitations of the steel production process has increased. Together with enhanced metallurgical understanding, this has enabled the widening of the dimensional ranges of new and existing products, and also enabled the design of new steel grades.
- Information was gathered concerning the design and dimensioning of structures made from direct quenched steels, and a manual published. This helps end-users of such steels to obtain the greatest benefits for their products.

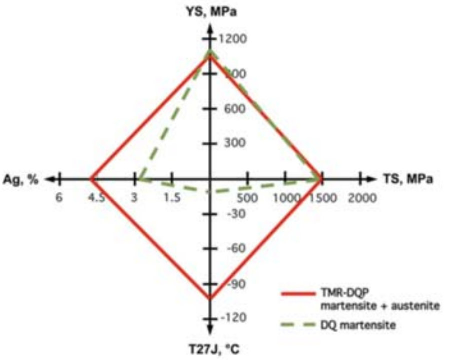

Figure 1. **Properties of the new steel concept, based on thermomechanical rolling combined with quenching and partitioning, compared with a fully martensitic direct quenched steel**

The main research themes on stainless steels were deformation mechanisms, grain size refinement and delayed cracking. The result highlights are described in the following.

The influence of chemical composition on stacking fault energy (SFE) was analysed using thermodynamic calculations. Microstructural studies carried out by electron backscatter diffraction (EBSD), transmission electron microscopy (TEM), X-ray diffraction (XRD) and other experimental techniques on various test materials showed that in low-SFE materials the dominant deformation mechanism was transformation to α' and ε martensites (Figure 2). Higher-SFE materials were stable against martensite formation, and mechanical twinning was observed (Figure 3). The effects of deformation mechanisms on the strain-hardening behaviour of steels were clarified. This knowledge is the key for optimisation of the mechanical properties of austenitic stainless steels, and was used in the development of new alloying concepts.

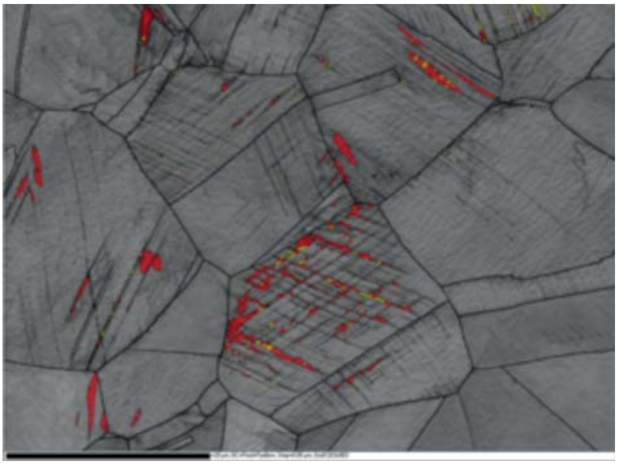

Figure 2. **EBSD image showing α' martensite (red) and ε martensite (yellow) in 10% tensile strained 15Cr-1Ni-9Mn austenitic stainless steel**

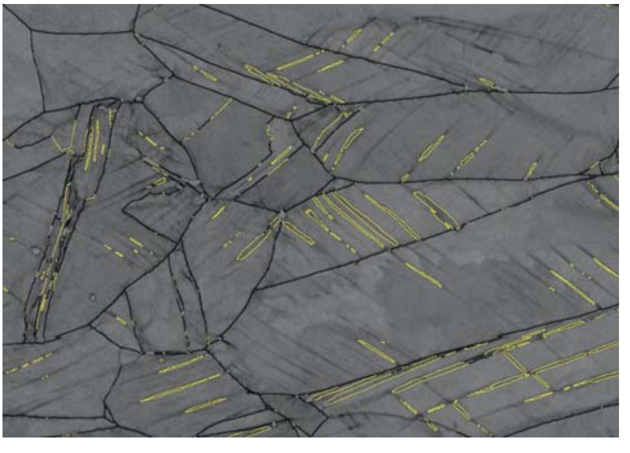

Figure 3. **Mechanical twinning in 30% tensile strained 17Cr-5Ni-6Mn austenitic stainless steel**

The influence of alloying and microstructure on the corrosion properties of low-nickel austenitic stainless steels was analysed and modelled, while a regression model was developed for predicting the pitting potential based on chemical composition, and used as a tool in developing new alloying concepts. The potential of grain boundary engineering to increase the corrosion resistance of low-Ni austenitic stainless steels was also investigated. This was demonstrated to allow a high carbon content in an austenitic stainless steel without the risk of sensitisation.

Thermomechanical processing of fine-grained austenitic steels was developed, and reversion, recrystallisation and grain growth kinetics were studied and modelled. These results are the basis for finding optimum processing parameters for thermomechanical processing. A study was made of the influence of grain size refinement on deformation mechanisms. It was found that superior mechanical properties can only be achieved with careful optimisation of both processing parameters and the chemical composition of the steel. On the basis of the results, optimised alloying concepts for fine grained steels were developed and tested. Furthermore, alloying with carbide- and nitride-forming elements such as niobium was found to be an effective method of limiting grain growth. Niobium alloying can therefore be used to enlarge the annealing process window, and thus substantially improves the industrial feasibility of the grain refinement process.

Another thermomechanical processing route was developed that makes use of twin formation during cold rolling and the stability of the twins during annealing. This can produce a good combination of yield strength and uniform elongation with barely any martensite.

Excellent results were obtained from studies of the delayed cracking phenomenon. Explanations were found for the effect of residual stresses, strain-induced α'-martensite and hydrogen content on the delayed cracking susceptibility of metastable austenitic stainless steels, particularly low-Ni grades: strain-induced martensitic transformation induces high residual stresses in the material, thereby increasing the susceptibility. High hydrogen content and high residual stresses explained the susceptibility of the low-Ni grades. Reducing the hydrogen content of the steel, for instance by heat treatment, efficiently reduces the risk of delayed cracking. Design guidelines for avoiding delayed cracking were developed and coupled with finite element forming simulations (Figure 4).

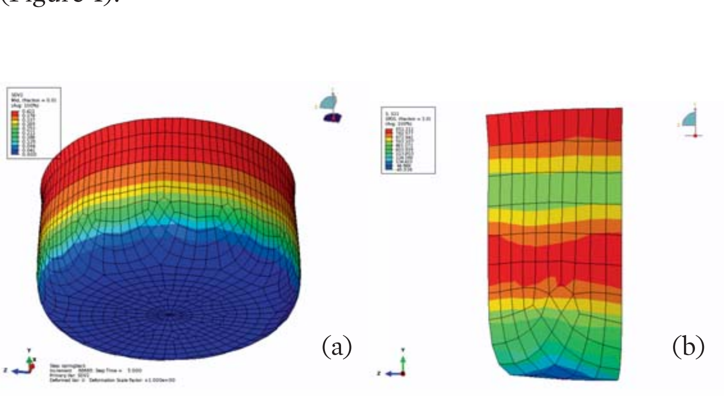

Figure 4. Prediction of (a) α'-martensite content and (b) residual stresses by finite element simulations. The modelling approach was coupled with the developed design curve concept in order to predict the risk of delayed cracking

Key publications

1. Kaijalainen, A., Suikkanen, P., Karjalainen, L.P. & Jonas, J.J. (2014), Effect of austenite pancaking on the microstructure, texture and bendability of an ultra-high-strength strip steel, Metallurgical and Materials Transactions A, Vol. 45, pp. 1273–1283.
2. Somani, M., Karjalainen, L.P., Misra, R.D.K. & Porter, D. (2014), On various aspects of decomposition of austenite in a high-silicon steel during quenching and partitioning, Metallurgical and Materials Transactions A, Vol. 45, pp. 1247–1257.
3. Suikkanen, P., Ristola, A.-J., Hirvi, A., Sahu, P., Somani, M., Porter, D. & Karjalainen, L.P. (2013), Effects of carbon content and cooling path on the microstructure and properties of TRIP-aided ultra-high-strength steels, ISIJ International, Vol. 53, pp. 337–346.
4. Kisko, A., Misra, R.D.K., Talonen, J. & Karjalainen, L.P. (2013),The influence of grain size on the strain-induced martensite formation in tensile straining of an austenitic 15Cr-9Mn-Ni-Cu stainless steel, Materials Science and Engineering A, Vol. 578, pp. 408–416.
5. Curtze, S., Kuokkala, V-T., Oikari, A., Talonen, J. & Hänninen, H. (2011), Thermodynamic modelling of the stacking fault energy of austenitic steels, Acta Materialia, Vol. 59, pp. 1068–1076.

Number of publications: 29 published, 2 submitted

Number of Doctoral Theses: 3 to be completed 2015

Number of Master's Theses: 12

Number of patent applications: 3

Networks and international co-operation

At the University of Oulu, transmission electron microscopy investigations in co-operation with Professor R. Devesh K. Misra, Director of the Center for Structural & Functional Materials at the University of Louisiana at Lafayette, USA, have been useful in elaborating microstructural details of the steels studied in this programme, and has led to common publications. Similarly, at Aalto, a 12-month visiting researcher programme to Georgia Institute of Technology – one of the top 10 universities in the field of engineering – resulted in the application of advanced characterisation methods and a joint publication. In another researcher exchange between the University of Oulu and Professor DeArdo at the Basic Metals Processing Research Institute in the University of Pittsburgh, a researcher was able to learn advanced microscopy techniques. Aalto University hosted a visiting researcher from Tohoku University in Japan for 12 months. Assistant Professor Puspendu Sahu from the Department of Physics, Jadavpur University, Kolkata, India visited Oulu and assisted in XRD technology transfer for the measurement of dislocation densities.

Applications & impact

Markets for the ultra-high-strength steels are expected to grow rapidly in the future. For both Outokumpu and Ruukki, the development of future generations of ultra-high-strength steels is a key theme in their differentiation strategies. For both companies, the results generated in the FIMECC LIGHT programme serve as a knowledge platform on which future steels will be developed. These steels will not only provide competitive advantage in existing markets, but will open totally new markets for steels.

PROJECT NAME

P 2 Novel Manufacturing Technologies for Innovative and Sustainable Solutions

The P2 project directly follows the FIMECC strategic vision, which is to gain a leading international position in the development of a future generation of advanced materials, structures and systems having reduced weight, increased performance, improved energy efficiency and reduced environmental footprint. The FIMECC SRA has identified the development of hybrid materials, and their assembly, joining and manufacturing technologies, as one of the important research focus areas. Consequently, the objectives of the P2 project included joining processes for ultra-high-strength steels, hybrid structures and dissimilar materials, as well as novel processing technologies for manufacturing of hybrids and other layered or sandwich materials. The research carried out during the P2 project is paving the way for further development of light and efficient structures and, consequently, more competitive future products.

The main research target in P2 was to study and develop novel manufacturing technologies for the fabrication of light and efficient structures for different products. The primary goal was to evaluate and improve manufacturing techniques applicable for next generation breakthrough materials by optimising the critical mechanical properties of the fabricated structures and components, and by increasing the functionality of materials or structures. A secondary goal was to shorten the manufacturing lead time, and to improve product quality and cost efficiency. The manufacture of potential material solutions – such as sandwich and cell panels having ultra-high-strength surface plates or hybrid metal-polymer structures for increased wear or impact resistance – has been evaluated and prototypes tested. A study has also been made of joining dissimilar materials by adhesion, clinching, hybrid-joining methods or advanced welding methods such as laser welding. The selected project highlights are presented in the following:

1. Ruukki full-metal sandwich panels: lightweight impact and wear-resistant panels and lightweight protection elements

Wear-resistant panels and protection panels were developed to a level of technological readiness for manufacture of the elements in agreed sizes. Welding tests, definition of welding parameters and basic mechanical tests were carried out by Aalto University. Later on, based on a separate applied research and development project for an international customer funded by Ruukki, a patent was applied for use of the wear-resistant sandwich structure in a particular type of transport application. The lightness of the panels opens up new possibilities for applications where weight reduction or portability needs to be combined with a wear-resistant surface.

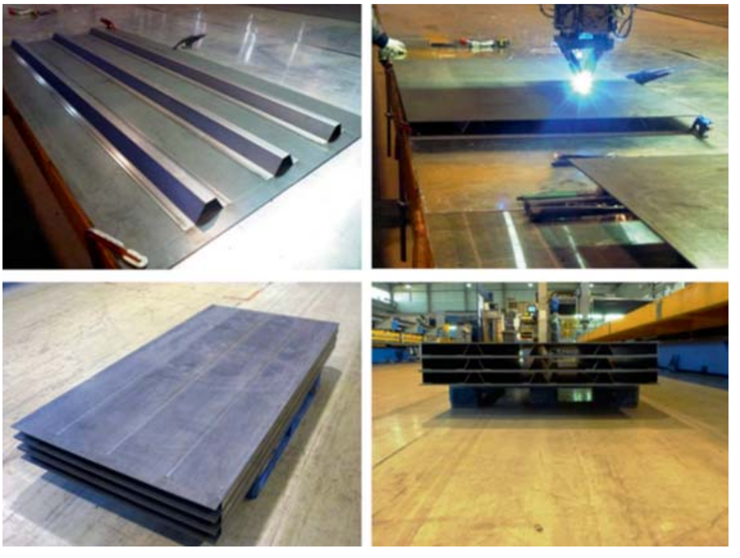

Figure 1. **Manufacture of impact resistant sandwich panel prototypes**

2. Ruukki lightweight panels for building industry

The joining of corrosion-resistant coated materials is challenging. Welding is unsuitable for most applications because it destroys the protective coating. A hybrid joining method was developed under the project, based on clinching and adhesive bonding that resulting in stiff, lightweight and airtight panels, the airtightness necessary for integrating ventilation into the panels. Joining tests, mechanical testing of joints and development of the tooling was made together with HAMK Sheet Metal Development Centre and BTM Scandinavia AB. The functionality of the panel in composite intermediate floors is further studied in a RFCS project coordinated by RWTH in Aachen.

3. Metso light and durable structures/TUT polymer/hybrid joining, durability testing

The focus was to evaluate new polymeric and hybrid material solutions for applications in heavy machinery. Several case studies were carried out during the project, covering various crusher components. New hybrid material solutions were evaluated for the new diesel engine motor power pack meeting the Tier 4 interim, Stage IIIB or MLIT step 4. The result of many engineering improvements, these new power packs now provide substantial fuel savings while significantly lowering the main emissions. In addition to fuel economy, the renewed engine modules offer better access for maintenance and longer air filter service intervals thanks to the improved air intake position. A new, stylish appearance comes as a bonus feature (Figure 2).

Figure 2. **New design and material solutions for the diesel engine power pack**

Other promising applications for the lightweight components were found in polymeric shields. The need for developing lighter shield components for jaw crushers leads to utilisation of a new construction material in Metso mineral crushers (Figure 3). The benefits and drawbacks of using polymeric and composite material components in a demanding process environment were carefully studied with TUT. The benefits were quite clear; the weight of the component system was reduced to half, and more compact components were easier and thus safer to open and lift during maintenance. However, the polymer applicability for components susceptible to heavy loading and sharp impacts needed to be studied first in the laboratory and later in field testing in the customer's equipment.

Figure 3. **Pictures of an old (left) and new shield construction**

Customer feedback from the first field tests was promising, but the real surprise for the designers was the excellent durability of the polymeric shields. In contrast to the sheet steel used previously, polymer can adapt to substantial loading without permanent deformation. The design of the shields was also completely renewed: with its two-fold and free forms, the shield appearance is now modern and streamlined. A study has been made of new polymers and hybrid materials on the basis of the good results of this pilot project. The first pilots have already led to the design of other, even more demanding hybrid material constructions which are currently under development.

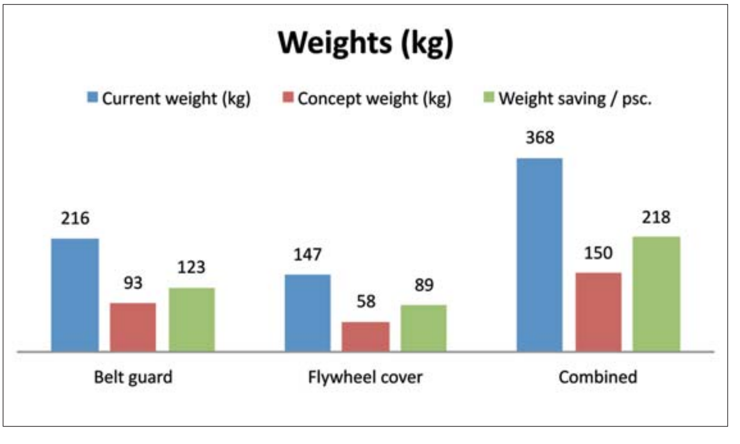

Figure 4. **The calculated weight savings of new shield components compared to old construction**

4. Fabrication and durability of steel-polymer hybrids for demanding applications (TUT)

A direct-adhesion manufacturing technique was studied and developed for fabricating complex hybrid components for high-wear processes. Proto components were fabricated and tested successfully together with Metso. The manufacturing technique will improve competitiveness by significantly simplifying the production method of even complex shapes and enabling constructions not feasible with conventional techniques.

The fabrication-based residual stresses of such products can be significant and have detrimental effects. A stress-optic measurement technique was developed in order to study and understand the interfacial behaviour of the hybrid components. The relatively simple technique can be used, for example, to study the role of surface treatments of the metal components on the residual stresses and durability of the hybrid structures.

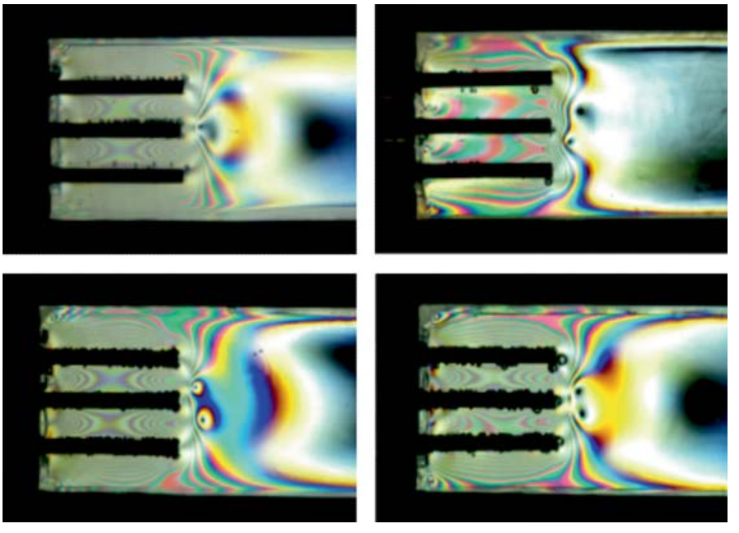

Figure 5. **Stress-optic measurements showing the effect of different surface treatments of the stainless steel plates on fabrication-based residual stresses in steel-epoxy hybrid components**

Key results

- New lightweight solutions have been introduced in mineral crushers and steel-based building components, with positive impact on the application and environmental footprint of these products. Reduced weight and good recyclability means fewer natural resources consumed and less waste generated during the life cycle of the product

- The solutions developed for ultra-high-strength steels and hybrid materials enable the design of new lightweight components with optimised properties; benefits are obtained over the whole life time of the product in terms of reduced energy consumption, reduced emissions and improved performance with integrated functionalities
- Developed design concepts and good understanding of the advantages and drawbacks of different joining methods have helped the industrial partners to identify new business opportunities and improve competitiveness in the global markets
- Improvements were achieved in manufacturing of hybrid material and dissimilar metal joints.

fimecc

FINAL REPORT 4/2014

PROJECT NAME

P 2 Novel Manufacturing Technologies for Innovative and Sustainable Solutions

CONTACT PERSON

MARKE KALLIO
METSO MINERALS OY

SAMI NUMMELA
RAUTARUUKKI OYJ

HANNU HÄNNINEN
AALTO UNIVERSITY

JYRKI VUORINEN
TAMPERE UNIVERSITY OF TECHNOLOGY

PARTICIPANTS (ORGANISATIONS)

METSO MINERALS OY
RAUTARUUKKI OYJ
AALTO UNIVERSITY
TAMPERE UNIVERSITY OF TECHNOLOGY

PROJECT DURATION

2009 – 2014

PROJECT VALUE (EUR)

2.700 MILLION

Main targets & motivation

- To obtain component weight savings in the range of 20–50%, which in turn improve cost- and energy-efficiency
- To understand the potential of lightweight hybrid and sandwich materials in novel material combinations and to improve the competitiveness of products through advanced material solutions
- To develop new breakthrough material solutions and joining technologies
- To acquire understanding and knowledge of special joining methods for high-strength steels, dissimilar materials and hybrid structures
- To gain a leading international position in conceptual design of new high-performance structural hybrid materials, in processing routes for high-performance structural hybrid materials, and in design guidelines for high-performance structural hybrid materials

In manufacturing competitive products, the complex demands associated with short lead-time, maximum cost-effectiveness and high quality need to be balanced against those of durability and structural integrity. Increasing importance has been attached in recent years to reduced energy consumption, total life-cycle assessment and environmental footprint issues, leading many manufacturers to select lightweight designs incorporating high-strength materials, and to adopt new approaches to production engineering. These demands for higher structural performance have brought a corresponding increase in the strength requirements for materials used in structural applications. The choice of structural materials that can be manufactured has been continuously widening, with sandwich-type or other thin-walled structural alternatives replacing thicker plate in some demanding load-bearing applications, and implementation of various forms of multi-material structures. The effective application of novel material technologies brings a clear competitive edge in metal and engineering industry.

Summary of clear results and deliverables

Novel material solutions provide strategic advantage and, in the current market turbulence, a way of standing out from the competition. This project has evaluated new structural material solutions made of dissimilar materials, and these are now proceeding to the productisation stage. Most particularly, important elementary knowledge has been accumulated on joining techniques for dissimilar materials by welding or adhesion, and on the durability of these joints for demanding applications involving fatigue and wear. The lighter weight of the full-metal sandwich panels creates new possibilities for applications where weight reduction or portability needs to be combined with a wear-resistant surface.

The project has brought a significant increase in knowledge concerning the relationship between processing routes for hybrid, composite and sandwich materials and their mechanical performance, and on the application of high-strength steels and hybrid materials in lightweight structures. The development of polymeric shield components less than 50% of the old design weight is one concrete example of the saving obtained, with the important added benefit of greater compactness allowing easier, and thus safer, opening and lifting during maintenance.

Key publications

1. Siltanen, J. et al. (2013), Laser-welded sandwich floor panel for marine container, Paper 702, ICALEO 2012.
2. Patent application no. 20116324, Rautaruukki 2013. http://patent.prh.fi/patinfo/tiedot.asp?NroParam=20116324&ID=X998446&Lng=ENG.

3. Orell, O., Kakkonen, M. & Vuorinen, J. (2013), Photoelastic stress evaluation and mechanical testing of stainless steel–epoxy hybrid, Tampere University of Technology DMS, Composites Week @ Leuven and TexComp -11 Conference.
4. Hirn, J. (2010), Suitability of resistance spot welding and laser welding for the production of all steel sandwich panels with ultra high-strength thin faces and a high-strength core. Master's thesis, Aalto University.
5. Gofman, I.V., Yudin, V.E., Orell, O., Vuorinen, J., Grigoriev, A.Ya. & Svetlichnyi, V.M. (2013), Influence of the degree of crystallinity on the mechanical and tribological properties of high-performance thermoplastics over a wide range of temperatures: from RT up to 250 °C, Journal of Macromolecular Science, Part B: Physics.

Number of publications: 7
Number of Doctoral Theses: 1
Number of Master's Theses: 4
Number of patent applications/patents: 1

Networks and international co-operation

- Ruukki lightweight building panel prototypes were manufactured together with BTM Scandinavia AB and delivered to RWTH in Aachen for further testing.
- Close collaboration was carried out between TUT and the Institute of Macromolecular Compounds, Russian Academy of Sciences (Vladimir Yudin, Iosif Gofman) relating to development and tribological testing of high-performance polymers for demanding applications.
- Aalto has carried out co-operation on friction stir welding of high-strength steels with Prof. Kokawa and Prof. Sato at Tohoku University, Japan.
- Prof. Hänninen has been a visiting professor at MIT, USA.

Applications & impact

New structural material solutions made of dissimilar materials have been evaluated and are now proceeding to the productisation stage. The solutions have found applications in very different fields; the rigid and lightweight high-strength steel panels are used for various structural purposes ranging from freight container floors to special modular panic rooms. Commercialised protection panels have been announced by Ruukki, see www.ruukki.com/ramor-panel. Polymers and polymer-metal hybrids have proven their durability, wear and impact resistance in laboratory testing, and can be used in highly demanding applications such as crusher structural components, and may even have application as wear parts. On top of this, however, the extensive elementary knowledge gained in this project means there are several other potential applications on the horizon. The results of P2 may be far-reaching, with the final impact being shown over the next 2–5 years through commercialisation of the results obtained.

The results have been communicated in the following seminars:

FIMECC 1st annual seminar, 19 November 2009, Tampere

- Halme, T., LUT: Miten paljon metallirakenteet voivat keventyä?

LIGHT 1st annual seminar, 8 October 2010, Technopolis, Tampere

- Vuorinen, J., TUT: Improvements with hybrid materials
- Hirn, J., Aalto: Suitability of resistance spot welding and laser welding for the production of all-steel sandwich panels
- Nuutinen, J., Rautaruukki Oyj: Kevyet yhdistelmärakenteet
- Lahtomäki, R., Metso Minerals Oy: Rakenteiden keventämisen hyötyjä ja haasteita

FIMECC 3rd annual seminar, 20 October 2011, Marina Congress Centre, Helsinki

- Hirn, J., Aalto: Analysis, optical deformation and strain field tests of laser-welded lap joints

FIMECC 5th annual seminar, 28 November 2012, Naantali Spa

- Orell, O.,TUT: Mechanical and photoelastic characterisation of polymer–steel hybrid structure

FIMECC 6th annual seminar, 20 November 2013, Rosendahl, Tampere

- Kallio, M., Metso Minerals Oy: Novel manufacturing technologies for innovative and sustainable solutions

PROJECT NAME

P 3 Innovative Design Solutions

The project set out to investigate basic failure mechanisms, measure performance characteristics and develop parameters and virtual modelling tools. The goal was to develop design analysis methods and failure avoidance strategies for new materials and lightweight fabricated structures. These research deliverables were consequently to enhance the use of new-era, high-strength steels in practical designs. The project involved characterisation of critical links between the properties of the initial materials, the manufacturing process and the performance of the fabricated component or structure, while a study was also made of innovative design concepts, including application-based design and integrated intelligence. A further, important issue was to influence international bodies responsible for design codes, so that old rules placing severe restrictions on high-strength steels could be modified on the basis of the results obtained.

RAUTARUUKKI/AALTO/LUT

Design normally involves the question of strain limits, a common problem during the design phase. The European steel design standard for steel structures, Eurocode 3, for example, currently allows a 5% strain limit for load-carrying structures. The project's study of the strain properties of Ruukki's Ultra-High-Strength Steels (UHSS) showed strains up to 100%. This will have a clear impact on design rules in the future, and extends the use of UHSS. The values were verified using digital image correlation, while developed use of the finite element method gave similar results.

A new type of hollow section fulfilling two strength classes showed full capacity in successful tests of cold-formed hollow sections, thus indicating the potential for more efficient structures. The HF welding method used in the manufacture of cold-formed hollow sections has been successfully tested with yield strength up to 700 MPa, clearly higher than existing grades.

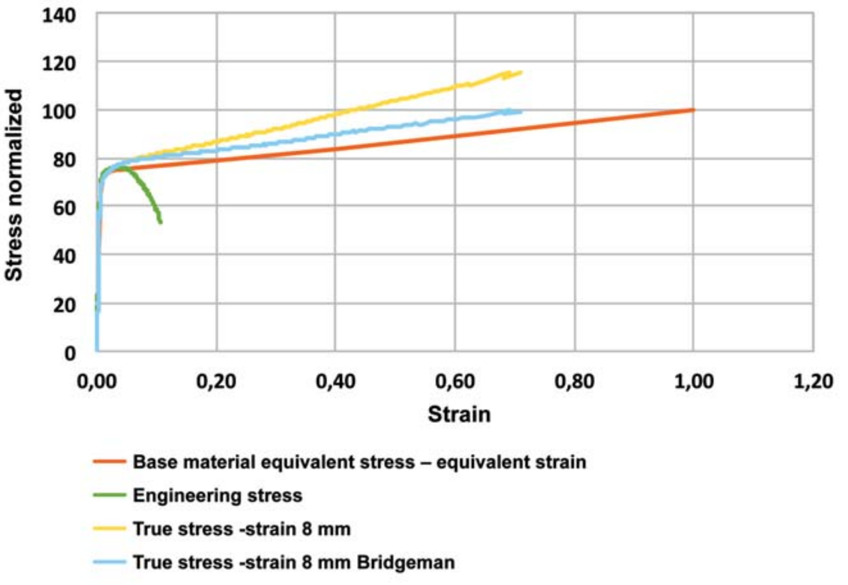

Figure 1. **Strain capacities of new high-strength steels**

The parameters of the GMAW process were adjusted to produce high quality welds for UHSS grade S960 QC. The experimental results proved that high fatigue strength can be reached without post treatments of welds under fluctuating loads, which means savings in fabrication cost and shortening of lead times. The requirements for static strength of joints made of S960 were also fulfilled, which is vitally important to the safe use of structures made of UHSS. Consideration must nonetheless be given to the softening effect due to welding, and to the high stress ratio, as both can reduce the capacity of welded joints significantly. Considering these limitations, the S960 QC can obtain potential weight savings of up to 60% compared to the conventional S355 steel grade.

The fatigue strength of the longitudinal production weld in cold-formed tubular sections made of high-strength steel proved sufficient for structures under fluctuating loading. For these tubes to acquire properties also beneficial to end users, handling of the components during the fabrication process must be carried out carefully according to the instructions. Tubular components and joints made of high-strength steels also proved to have excellent static strength, offering a wide range of optimal solutions for weight-critical applications.

One option for improving the fatigue strength of welded structures is high-frequency mechanical impact (HFMI). The increasing popularity of HFMI treatment brings a need to standardise the procedure and corresponding quality measures, and to determine the level of improvement in fatigue strength for different loading conditions. A comprehensive proposal for fatigue assessment of HFMI-treated welded steel structures has consequently been developed during the project, and published by the International Institute of Welding. A key aspect is that the level of improvement increases with increasing steel strength. This makes the use of high-strength steels in fatigue-critical welded applications significantly more attractive.

Although the bonded/bolted hybrid joint provides improved fatigue endurance compared to welded joints or plain bolted joints, understanding of the fatigue behaviour of these joints has been limited. The research focused on obtaining a fundamental understanding of the failure mechanisms in the bonded and clamped interfaces of the joint. New experimental and analytical methods useful in the product development and design of bolted/bonded hybrid joints have been introduced and applied.

METSO/AALTO

A simulation software was developed to model jaw crusher dynamics. Input comprises the crusher material and geometrical parameters, and stone impact loads. The software performs the eigenmode analysis and transient dynamic analysis of the jaw crusher, calculates its frequency response function, and determines an optimal dual mass balancing of the jaw mechanism. A jaw crusher may be balanced by two balancing masses rotating in opposite directions. Careful design of the balancing masses may remove approximately 90% of the inertial forces and vibration amplitudes due to the imbalanced jaw mechanism. Dual mass balancing provides several benefits, such as lower stress, vibration and noise levels of the machine, and an increased fatigue life. In future machines, the lowest resonance speed may also be exceeded by virtue of the lower vibration excitation.

In the design phase of the C 120 jaw crusher, FEA-verified design calculation modules were developed for some critical components of the crusher. The pitman is the heart of a jaw crusher and the most critical component of the crushing process. For this reason the design module of the open pitman is very important, since it shortens the strength calculation process and includes significant design criteria information. The weight of the design is optimised by selecting proper cross-sectional parameters and a good web-plate shape for different crushing loads. Optimal casting release dimensions can be taken into account in a preliminary phase. The new open pitman has no casting cores, doing away with the need for extra holes for removing the sand. This also means a longer fatigue life and less weight. An easier manufacturing process means a better quality and more accurate dimensions of the pitman with minimum manufacturing cost. The multi-directional nature of the honeycomb structure provides better support for the wear parts. Less crushing energy goes to the structures and more into breaking the stones, resulting in enhanced crushing productivity.

Component mode synthesis was employed in the dynamic analysis of a portable stone crusher feeder unit. In the first stage, the multibody dynamics approach and finite element method were compared in a stress analysis of the frame during dynamic loading. The results revealed that both approaches can predict the stress history. In the second stage, random vibration analyses were used to find statistical properties of displacements under dynamic loading. The multibody simulation was performed in time domain and random analysis in frequency domain. The statistical results of these, such as the standard deviation of the vertical displacement, were compared and found to be in relatively good agreement. In the third stage, component mode synthesis was extended to describe geometrical nonlinearities. This extension is intended to make the approach suitable for optimisation.

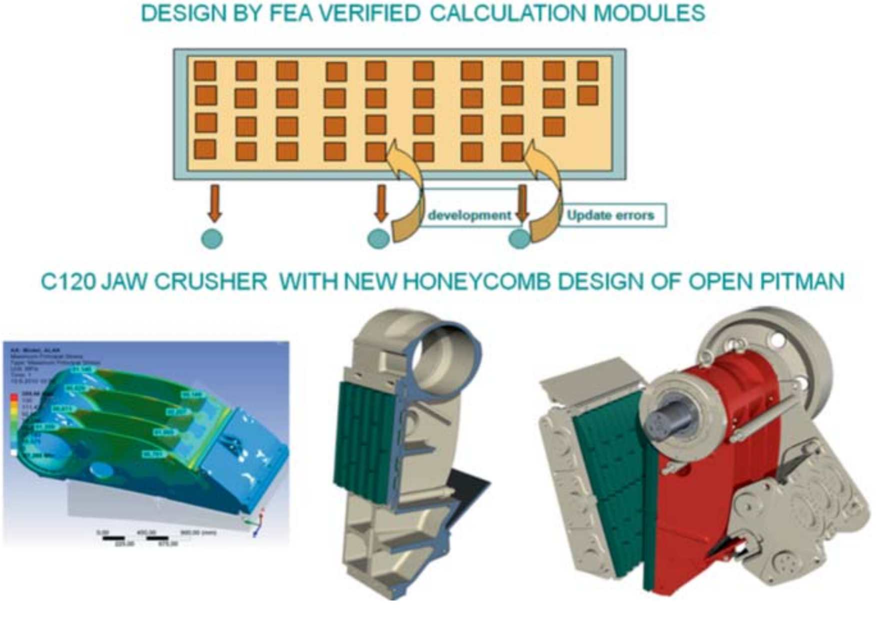

Figure 2. **Design by FEA-verified calculation modules significantly shortens the design process**

PROJECT NAME

P3 Innovative Design Solutions

CONTACT PERSON	PARTICIPANTS (ORGANISATIONS)	PROJECT DURATION
ILKKA VALKONEN RAUTARUUKKI OYJ **GARY MARQUIS** AALTO UNIVERSITY	**RAUTARUUKKI OYJ** **METSO MINERALS OY** **STX FINLAND OY** **AALTO UNIVERSITY** **LAPPEENRANTA UNIVERSITY OF TECHNOLOGY** **TAMPERE UNIVERSITY OF TECHNOLOGY**	**2009 – 2014** PROJECT VALUE (EUR) **7.400 MILLION**

Main targets & motivation

Increase of material strength in machine design is usually limited by fatigue. Fatigue-related research is vital if the use of novel Ultra-High-Strength Steels (UHSS) is to be increased. One part of this research is the development of bonded joints.

The development of new design rules for UHSS in general steel construction industry, which can be used by the majority of designers. Current strain limits in standards are not valid for UHSS. Consequently, their use in the design of structures using UHSS is difficult or practically impossible in traditional engineering, especially project engineering.

Though use of cold-formed Ultra-High-Strength Steel hollow sections in steel construction has proved possible, these are not recognised by existing standards, and the rules are inapplicable even where High-Strength Steel (HSS) is used.

Virtual design tools for lightweight mobile structures subjected to harsh service loading conditions are of great importance in practical mechanical engineering. These will necessarily involve the development of analytical, computational and multibody methods for determining displacements, loads and forces of lightweight mobile structures based on kinematics, dynamic simulation tools and stress analysis. Design can also make use of FEA-verified calculation modules.

Results Extensive data base from test results for creating new design rules and standards for the emerging new materials, especially for joint design of constructions made of UHSS. The information is mainly distributed through articles in scientific journals.

Improved jaw crusher technology, including tailored dynamic simulation software and a balancing method for jaw crushers, FEA-verified design calculation modules speeding up the strength calculation process, and a new open pitman design with a honeycomb structure and enhanced crushing productivity.

Key publications

1. Nykänen, T., Björk, T. & Laitinen, R. (2013), Fatigue strength prediction of ultra-high-strength steel butt-welded joints, Fatigue & Fracture of Engineering Materials & Structures, Vol. 36, Issue 6, June 2013, pp. 469–482, doi: 10.1111/ffe.12015.
2. Nykänen, T., Björk, T., Mettänen, H., Ilyin, A.V. & Koskimäki, M. (2014), Residual strength at −40 °C of a pre-cracked cold-formed rectangular hollow section made of ultra-high-strength steel – An engineering approach, Fatigue & Fracture of Engineering Materials & Structures, Vol. 37, Issue 3, March 2014, pp. 325–334, doi: 10.1111/ffe.12117.
3. Marquis, G.B. & Barsoum, Z. (2014), Fatigue strength improvement of steel structures by high-frequency mechanical impact: proposed procedures and quality assurance guidelines, Welding in the World, Vol. 58, Issue 1, pp. 19–28, doi: 10.1007/s40194-013-0077-8.
4. Marquis, G.B., Mikkola, E., Yildirim, H.C. & Barsoum, Z. (2013), Fatigue strength improvement of steel structures by high-frequency mechanical impact: proposed fatigue assessment guidelines, Welding in the World, Vol. 57, Issue 6, pp. 803–822, doi: 10.1007/s40194-013-0075-x.
5. Kurvinen, E., Dmitrochenko, O., Matikainen, M. & Mikkola, A. (2012), Comparison of Deterministic Multibody Simulation and Random Analysis in a Linearised Model of a Vibratory Feeder, Proceedings of the 11th Finnish Mechanics Days, 29–30.11.2012, pp. 101–107.

Number of publications: 14 submitted

Number of Doctoral Theses: 2

Number of Master's Theses: 9

Number of patent applications/patents: 2

Networks and international co-operation

Co-operation in the field of fracture mechanics has been built between Ruukki, LUT and Kielce University of Technology (Politechnika Świętokrzyska). The visit of Professor Andrzej Neimitz from Kielce at Lappeenranta University of Technology.

Professor Gregorz Glinka from University of Waterloo in Canada as a FiDiPro visiting fellow researcher at Aalto University.

Applications & impact

Results from UHSS elongation tests gave material properties used in instructions for designers, and which will be used in international meetings to develop and improve new design guidelines and rules applicable also for UHSS.

Results from tests of cold-formed hollow sections can be used in revision work for European steel standards, and thus enable the use of higher-grade hollow sections in steel constructions.

While the use of ultra-high-strength steels is limited by fatigue in welded structures, the results of the project promise more advanced and cost-efficient fatigue design in the future.

The dynamic simulation software and multibody models can be used in the jaw crusher design phase to improve dynamic performance and balance. Virtual tool training for design engineers can be given, and design criteria developed for lightweight modular structures. The good commercial success of the new pitman design means that this type of pitman structure will be updated to a whole series of jaw crushers of different sizes. In the one hundred years and more of history in jaw crusher technology, this invention is a significant step.

PROJECT NAME

P4 Environmental Footprint

The Environmental Footprint project focused on finding ways of guiding industrial product design and development towards sustainability, especially from a product-centric point of view. The main target of the product design process is to develop new products that bring added value to customers, thereby improve economic business opportunities. It is nonetheless vital, and as early as at the design phase, to understand the effects of design decisions on the sustainability of the product. The project studied how material efficiency and recyclability were taken into account during the product design process, and identified the drivers behind sustainability.

Noting early on in the project that there was no actual need for new product design tools or software to enhance sustainability or material efficiency, a decision-making roadmap was developed instead to help with any sustainability issues in the design process. The roadmap for product designers, Elinkaariarviointi tuotesuunnittelussa / Life-cycle Assessment in Product Design, describes sustainability issues compatible with design processes described by the designers themselves.

Another important aspect in the project was the business argumentation for product sustainability. Improved sustainability, more than merely adding cost to the product, can be an important means of differentiating in the markets and gaining market share. The guide Elinkaarinäkökulma liiketoiminnan kehittämisessä/Life-cycle Perspective in Business Development will help to show the benefits of an improved environmental progress in business using examples from industry, and give practical advice on how to employ environmental aspects in sales argumentation. Both guides are available.


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Opas teräs- ja konepajateollisuudelle


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Aalto University
Elinkaariarviointi
tuotesuunnittelussa
Opas metalli- ja konepajateollisuudelle

PROJECT NAME

P4 Environmental Footprint

CONTACT PERSON	PARTICIPANTS (ORGANISATIONS)	PROJECT DURATION	PROJECT VALUE (EUR)
MARKE KALLIO METSO MINERALS OY **ILKKA SORSA** **SAMI NUMMELA** RAUTARUUKKI OYJ **KARI HEISKANEN** **NANI PAJUNEN** AALTO UNIVERSITY	**METSO MINERALS OY** **RAUTARUUKKI OYJ** **AALTO UNIVERSITY (AALTO)**	**2009–2014**	**0.900 MILLION**

Main targets & motivation

Introduction

All products and services have an environmental impact during their production, use and disposal. Production-related environmental policies have tended to focus on large point sources of pollution, such as industrial emissions and waste management. However, the huge overall amount and variety of products and materials, and the complexity of the value chain associated with their production, can create difficult or unmanageable environmental problems. The environmental impacts result from the whole life cycle of the product. Even if a product can be designed perfectly, it might be used and disposed of inappropriately, resulting in significant negative environmental impacts. On the basis of increasing environmental problematic, key aims in the European Union's future policies and legal framework will include sustainable development and associated sustainable production, consumption and sustainable industrial development.

A life-cycle approach can lead to improved environmental performance of industrial products and processes. This includes higher material and energy efficiency and avoided waste management costs through increased recycling, potential industrial symbiosis activities and reduced waste generation. Life-cycle thinking and associated methodologies, e.g. LCA[1], can provide much useful information for decision-making at company and plant

[1] LCA is a useful approach if the data used is created from actual system models, since it is based on environmental management standards concerning the principles and framework for an LCA (ISO 14040) and the requirements and guidelines for LCA (ISO 14044).

level. In brief, life-cycle thinking can significantly improve understanding of the overall environmental performance of product and production systems covering all industrial processes and material and energy flows. The aim of a life-cycle approach is to understand and improve the sustainability of a product. The study should be carried out as early as possible, in other words as soon as the design process begins and first decisions are made. Opportunities to effect changes in product design decrease over time. Co-operation between all actors in the supply chain for the product's entire life cycle is also important. Nonetheless, to be considered a serious design tool the life-cycle approach must convince business decision-makers of its ability to add value for the customer and/or save money, and thereby improve economic business opportunities. One of key motivations of the project was to address just this.

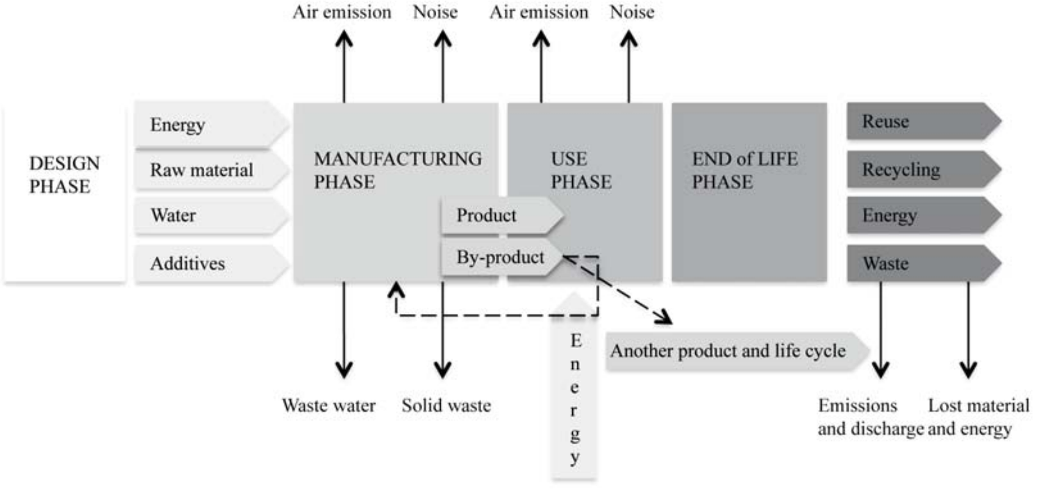

Figure 1. **Life cycle of the product**

Objectives

The first objective of the Environmental Footprint project was to investigate the environmental footprint of the lightweight solutions developed. The research work was divided into three phases: the product design and production phase, the use phase and the end-of-life (EoL) phase. The LCA metric was used to compute the environmental footprint during the product's life cycle. The second objective was to investigate the value chain factors influencing the life cycle of the lightweight structures, and to create tools for designers for optimising environmental efficiency, from initial material selection until the end-of-life (EoL) phase in the value chain.

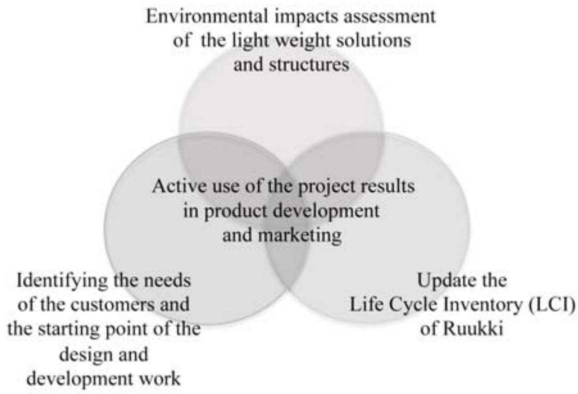

Figure 2. **Initial objectives of the project**

Goals:	Progress	Results
Goals: (1) Update the databases used by LCA to reflect the Finnish industry practices and making LCA models and case studies for environmental impact assessment. (2) Identifying the needs of the customers and solution and product development management in order to integrate the life cycle thinking during planning / engineering stage (3) The goal is to add business value, to promote LCA based marketing arguments and advantages of light weight solutions and to identify new business opportunities for lightweight solutions.	Milestone I / Life cycle thinking (1) Problem mapping (2) Background (Literature and FINLCA) (3) Research cases / Metso, Ruukki	Result I / Life cycle thinking Metso: – LCA for C106 jaw crusher and Lokotrack LT106 mobile crushing plant completed and results reported – LCA for cone crusher GP11F completed Ruukki: – Heavy transportation / savings in the net weight of the vehicle, saves fuel and decreases CO_2ekv emission – Environmental requirements in construction are increasing / Ruukki's energy panels
	Milestone II / Environmental footprint, working methods (1) Gabi training course (2) Literature research	
	Milestone III / Environmental impact (1) LCA tools for planning / Master´s thesis (2) LCA case in industry / Metso case (3) LCA case in industry / Ruukki case	
Technical goals: (1) To develop simple but suitable LCA model for representative light weight solutions and to test it in case studies (2) To prepare fact book for argumentation of business values and advantages of light weight solutions in different kind of structures	Milestone IV / Cooperation (1) Workshops	Result II / Guidebooks Guidebook / roadmap (2012) for the designers: *Life cycle assessment in product design.* Guidebook / roadmap (2014) for the product management teams and sales&marketing: *Life cycle perspective in business development.*
	Milestone V / Business cases (1) LCA models and case studies in environmental footprint assessment of lightweight solution (2) Business values and advantages of light weight solutions	
	Milestone VI / Academic research (1) Conference presentations (2) Scientific publications	Result III / Publications & presentations Master´s thesis (1), Licentiate thesis (1), journal articles (5), Conference articles (5)

Figure 3. **The structure of the project**

Results

The daily work of product designers includes, among others, concept and structural design on the basis of the product's application requirements, machine design and FEM analysis, component dimensioning and selecting the suitable materials. It also includes making decisions on the product life cycle, and providing life-cycle-based internal information for managerial decision-making. Most decisions – and these also affect the material efficiency and recyclability of products – are made by the designers, with the important environmental impacts often locked at an early phase of product design. Much of the design process also focuses on improving existing products rather than designing something entirely new, meaning that freedom of choice regarding sustainability is limited accordingly.

A product development project can be divided into distinct and successive phases, divided by decision-making gate points at which any project may be terminated. During the project it was noted that the companies studied did not especially consider environmental issues or material efficiency at any of the gates between the phases.

In practice, defining the product configuration involves selecting alternative components and modules from a current product library. When heading towards more sustainable products, every item of the product library should include life-cycle information, such as the calculated energy savings for Ruukki's sandwich panels [2]. This kind of accurate information allows effective decisions to be made on improving the environmental impacts of products.

It was evident from the project workshops that product managers are pivotal in communicating customer needs and market trends to the designers. Designers are constrained in their decision-making by the boundary conditions dictated by product functionality, material properties, material and component costs and availability, planned end customer price and tight timetables. Materials and components for new product designs are selected mainly on the basis of their performance and price, and not from a sustainability perspective.

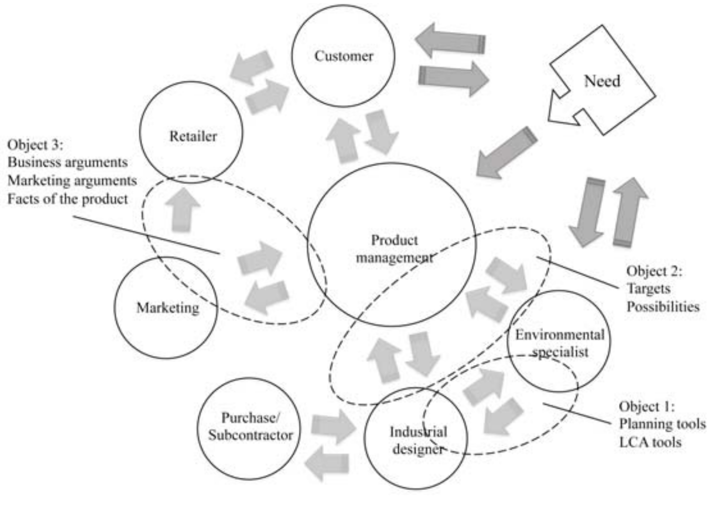

Figure 4. **Roles in the design process (Sahi-Pajunen & Sorsa, 2012)**

[2] http://www.ruukki.co.uk/Products-and-solutions/Building-solutions/Sandwich-panels (2.6.2014).

Interaction throughout the value chain would yield important information. Development work targets when designing a new product result from the strategic choices of company management, from customers mediated by product managers, or from project managers themselves. Information flow, including internal and external co-operation throughout the value chain, is critical; it was noted that any failure in this regard leads to environmentally good designs seldom being recognised as marketing arguments.

It was noted early on in the project that there is no actual need for new product design tools or software to enhance sustainability or material efficiency. Instead, a decision-making roadmap was developed to help with sustainability issues in the product design process. The roadmap for product designers, *Elinkaariarviointi tuotesuunnittelussa / Life-cycle assessment in product design*, describes sustainability issues compatible with the design processes described by the designers themselves.

The target of the roadmap was to present product designers with an approach based on life-cycle thinking, and to use concrete examples to show how to use this kind of approach in their own design processes. The idea was to steer thinking and discussion on product development in order to increase the awareness of environmental issues being a continuing process.

Discussion of sustainability issues interested not only engineers but marketing and sales people, too. Environmental information can be used in sales argumentation, and hence serve to increase environmental understanding on behalf of customers. A further guidebook, *Elinkaarinäkökulma liiketoiminnan kehittämisessä / Life-cycle perspective in business development*, was prepared as an aid to highlighting sustainability issues in business argumentation. It is important to share environmental facts, based on measurements and research, with all interest groups. Improved sustainability, more than merely adding cost to the product, can be an important means of differentiating in the markets and gaining market share.

Summary of clear results and deliverables

Guidebook/roadmap (2012) for designers: *Elinkaariarviointi tuotesuunnittelussa Life-cycle assessment in product design*.

Guidebook/roadmap (2014) for product management teams and sales&marketing: *Elinkaarinäkökulma liiketoiminnan kehittämisessä /Life-cycle perspective in business development*.

Metso

- LCA for C106 jaw crusher and Lokotrack LT106 mobile crushing plant completed and results reported (2010–2011).
- LCA for cone crusher GP11F completed (2011).

Ruukki

- Life-cycle assessment of Ruukki special steel products (Raahe), 2011–2012.
- LCI: Updating environmental data according to significant process improvements in Raahe production completed 2013.

Key publications

1. Pajunen, N. & Heiskanen, K. (2014), Take up the gauntlet: design for recycling! XXVII International Mineral Processing Congress, IMPC 2014, 20–24 October 2014, Santiago, Chile. Conference article and oral presentation.
2. Guidebook/roadmap (2014), for product development teams: Elinkaarinäkökulma liiketoiminnan kehittämisessä / Life-cycle perspective in business development.
3. Guidebook/roadmap (2012), for designers: Elinkaariarviointi tuotesuunnittelussa / Life-cycle assessment in product design.
4. Kujala, P. (2012), Tuotesuunnittelijan työkalu ja tuotteen elinkaaren aikaiset ympäristövaikutukset, Master's thesis, Aalto University.
5. Tirranen, J. (2012), Process control in track-mounted crushing and screening plants. Master's thesis, Tampere University of Technology, Automation Technology.

Number of publications: 7

Number of Licentiate Theses: 1

Number of Master's Theses: 2

Networks and international co-operation

Results of the Environmental Footprint project were presented at many international conferences during the LIGHT programme period (2009–2014).

Number of conference publications/presentations: 5

Participatory workshops held 2010–2013: 3

Participant companies: Metso Minerals, Metso Paper, Metso Corporation, Metso Power, Rautaruukki plc, Ruukki Metals Ltd, Cargotec Finland Ltd, Cargotec Corporation, Konecranes plc, Outokumpu Ltd, Outotec plc. Participants (approx. 20–25 persons) were mainly from industrial design, sales and marketing, communication and environmental departments.

Participant universities: Aalto University.

Applications & impact

Internal training sessions and pilot projects are used in both companies to boost competence in life-cycle thinking. Daily work at all business levels is nowadays supported by increased awareness of the potential environmental and other impacts associated with a product or service at all stages of its life cycle. Both customers, on the one hand, and product development, internal and external communications, sales and product support organisations on the other, are able to benefit from the project results.

Both companies have increased their ability to produce life-cycle assessments for their customers and stakeholders. Excellent examples of this are Metso's method of communicating the results of life-cycle assessment for the Lokotrack LT106 mobile crushing plant to all stakeholders, and Ruukki's method for adding streamlined LCA analysis to the service portfolio of technical customer service. The results of the project will help both companies to stand out from their competitors, and to provide their customers with new value-added services.

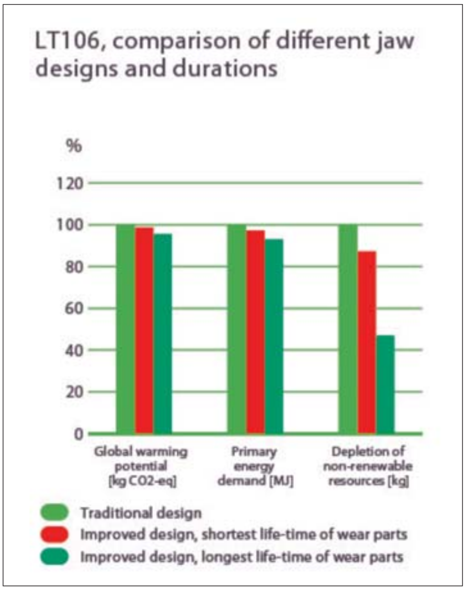

Figure 5. **Comparison of different jaw designs and durations, Lokotrack LT106**

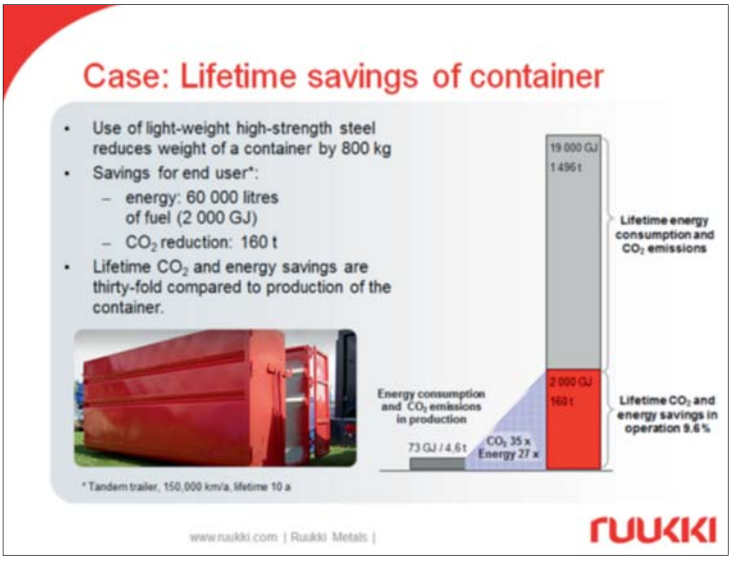

Figure 6. **LCA based information to customers and stakeholders**

PROJECT NAME

P5 Low-density Material Solutions

This project focused on the development of low-density material systems and their applications in mechanical and infrastructural engineering fields. The target was to obtain a deep understanding of the material systems and their processing and, consequently, to improve cost- and energy-efficiency of applications made from the systems. The material systems included were fibre-reinforced plastics (FRPs) and hybrids of FRPs and concrete.

One of the prerequisites when there is need for high mechanical properties in a composite laminate structure is straight fibre alignment. In the vacuum infusion process the state-of-the-art reinforcements have been Non Crimp Fabrics (NCFs) which Ahlstrom is producing with the well-proven warp knitting technology. These fabrics, however, suffer to a greater or lesser degree from pronounced fibre undulation. With this as a background, Ahlstrom set a target of developing a production technology for reinforcements that would leave the yarns straight, while simultaneously providing processing properties that customers would be willing to accept, at a competitive price level. Ahlstrom, supported by the project, has indeed been able to develop a new type of reinforcement that is anticipated to fulfil the objectives. The new technology is based on thermoplastic binders, and an innovation facilitating liquid resin penetration into extremely thick laminate structures. The actual development work was carried out exclusively within Ahlstrom. Bringing this new material to market demands extensive testing of chemical compatibility of the materials, and of the processing characteristics and mechanical performance of the laminates. This has been supported by a **Tampere University of Technology** MSc thesis on binder compatibility analysis, and by an **Aalto University** PhD investigation into fatigue performance of laminates made of NCF and new reinforcements. After successful initial tests, the first version of this new reinforcement was launched on the market at the end of 2013. The target application is wind energy blade structures, where ever-growing dimensions ask for extreme mechanical performance combined with lightness. Other composite structures will also benefit from the new reinforcement type.

At **Outotec**, a revolutionary new type of reactor for the metals processing industry was developed for utilising low-grade raw materials that are currently not economically feasible. The equipment was designed as a hybrid concrete/FRP structure, and its performance evaluated through CFD calculations and experimental tests in pilot scale. The reactor's construction methods and materials were investigated in co-operation with **Aalto University**. The relevant properties, such as long-term strength of FRP materials and wear resistance, were thoroughly investigated by Aalto University and by **Tampere University of Technology**. The multidisciplinary development approach enabled the acquisition of a sound basis for the techno-economical evaluation of the novel reactor concept.

At **Wavin-Labko**, the main goal was to obtain a better understanding, with modelling capability, concerning the short-term and long-term mechanical properties of underground FRP tanks, and to acquire economic benefit by optimising FRP laminate construction to meet the requirements of operational conditions. To arrive at the design basis and enable modelling it was necessary to define the loads applied to underground tanks. This was achieved in full-scale field tests. Laminate properties were tested in laboratory conditions, for example with water exposure tests and different kinds of creep tests. Testing was carried out in co-operation with **Tampere University of Technology**. Studies were also carried out at **Aalto University** on the use of peel plies. The results of the project enable Wavin-Labko to design a laminate construction more accurately for a given purpose, and allow the development of a new sandwich construction and production method for application in filament-wound FRP tanks.

Ekin Muovi and **Kevra** co-operated in the development of infrastructural applications made from FRPs. Both design principles and infusion-based processing methods applicable for large FRP structures were developed in the project. A pedestrian bridge was used as an example application and demonstrator for the technologies. The demonstrator bridge was successfully designed, manufactured and tested during the project. The work carried out by the companies was supported by processing and mechanical tests performed at **Tampere University of Technology** and **Aalto University**.

At **Meteco**, the main goal was to develop new tooling concepts for composite industry. The development work resulted in two novel solutions that were patented.

Figure 1 illustrates applications and activities of participating companies that have served as a motivation and support for the research carried out in the universities.

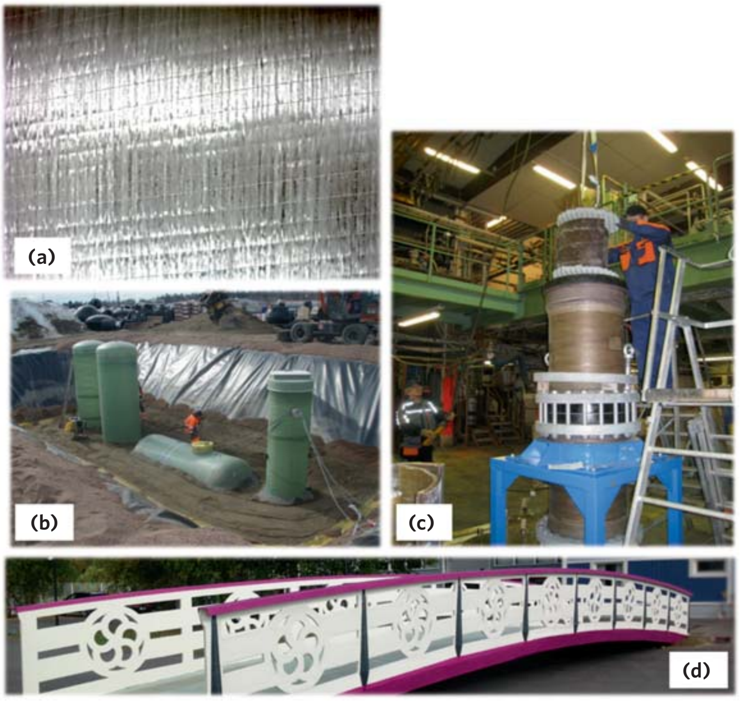

Figure 1. **Applications and activities of the participating companies: (a) new reinforcement product developed by Ahlstrom, (b) Wavin-Labko full-scale field test of an FRP tank, (c) Outotec test reactor, (d) FRP demonstrator bridge developed by Ekin Muovi and Kevra**

PROJECT NAME

P5 Low-density Material Solutions

CONTACT PERSON	PARTICIPANTS (ORGANISATIONS)	PROJECT DURATION
ERKKI LAPPI EKIN MUOVI OY **OLLI SAARELA** AALTO UNIVERSITY	**AHLSTROM OYJ** **OUTOTEC (FINLAND) OY** **EKIN MUOVI OY** **KEVRA OY** **WAVIN LABKO OY** **METECO OY** **AALTO UNIVERSITY** **TAMPERE UNIVERSITY OF TECHNOLOGY**	**2010 – 2014** PROJECT VALUE (EUR) **3.300 MILLION**

Main targets & motivation

The objective of the project was to build knowledge of existing and new low-density material systems for highly demanding applications. The material systems covered were fibre-reinforced plastics (FRPs) and hybrids of FRPs and concrete. The main targets were to find material systems, production methods and structure solutions enabling cost- and energy-efficient applications. Research related to processing characteristics and mechanical performance of the FRP systems formed an essential part of the work.

Results

The research into unidirectional glass fibre reinforcements was aimed at finding the effect of reinforcement structure on mechanical performance of the end product (laminate), and to find a reinforcement structure with improved performance when compared to current state-of-the-art reinforcements. Key findings and results were as follows:

- Laboratory equipment for studying the effects of reinforcement and processing parameters on laminate properties was designed and built, and successfully used in testing of the reinforcements
- Related to the development of a new reinforcement structure, a successful study was carried out on the effects of material components on processing and mechanical performance of the end laminate

- A specimen and methodology were successfully developed for fatigue testing of unidirectional glass-fibre-reinforced laminates
- A comprehensive test programme was successfully performed to find the effects of reinforcement parameters on the fatigue performance of unidirectional laminates
- A new reinforcement was successfully developed by Ahlstrom (Figure 1).

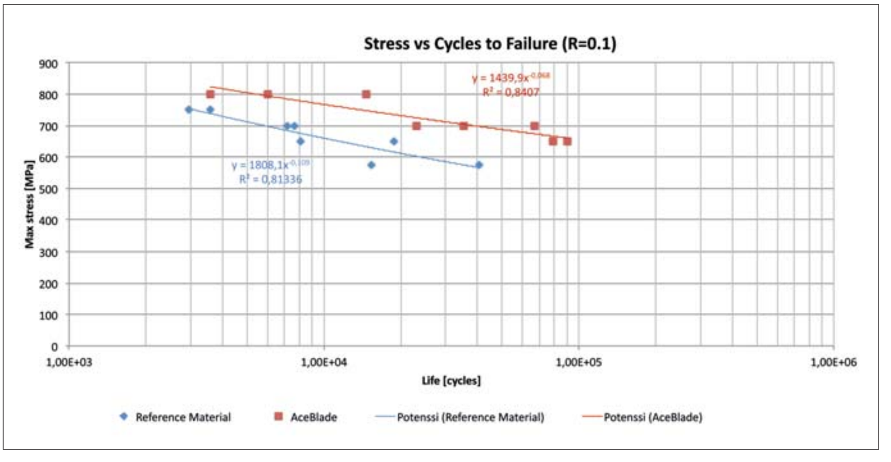

Figure 1. **Fatigue characterisation of a unidirectional glass-fibre-reinforced laminate with a new (red) and conventional stitched reinforcement (blue)**

The research on reactor structures for the metals processing industry was aimed at finding structure solutions and material data for a new type of reactor structure. Key findings and results were as follows:

- Successful analysis of applicability and efficiency of optional structure solutions
- Successful analysis of applicability and efficiency of optional concrete/FRP wall structures
- Erosion wear tests under industrially realistic conditions were performed in a test reactor at elevated temperature and in an acid environment with sand as erosive particles
- A comprehensive test programme was planned and realised for determining long-term strength properties of potential FRP structures in a relevant environment

– A sound basis was created for the techno-economical evaluation of the novel reactor concept.

The research related to infrastructural applications was aimed at finding design principles and processing methods for large FRP structures. Key findings and results were as follows:

– Full-scale field tests were successfully conducted to find realistic loads applied to underground FRP tanks

– Laminate testing was successfully performed to find relevant material data for underground tank applications

– Successful evaluation of applicability of peel plies as a surface treatment method for laminated joints

– Successful development of design principles and processing methods for large FRP structures, such as pedestrian bridges.

Key publications

1. Siljander, S. (2013), Effects of material components on properties of a composite laminate, MSc thesis, Tampere University of Technology, (in Finnish).
2. Bergström, R. & Korkiakoski, S. (2014), Non-stitched UD materials in the resin infusion process: Maximising the mechanical performance of UD materials for wind turbine blades, Wind Turbine Rotor Blades, 6th Technical Conference, 2–3 July 2014, Essen.
3. Salimi, Y. (2013), Structural optimisation of tower-like reactor of reinforced concrete in mining industry. MSc thesis, Aalto University, Department of Civil and Structural Engineering, 2013, (in Finnish).
4. Suihkonen R. (2014), Erosion wear of glass-fibre-reinforced vinylester, Nordtrib.
5. Kanerva, M. & Saarela, O. (2013), The peel ply surface treatment for adhesive bonding of composites: A review, International Journal of Adhesion and Adhesives, Vol. 43, pp. 60–69, http://dx.doi.org/10.1016/j.ijadhadh.2013.01.014.

Number of publications: 5, 3 submitted

Number of Doctoral Theses: 1 to be completed 2014, 1 to be completed 2015–16

Number of Master’s Theses: 9

Number of patent applications/patents: 4

Networks and international co-operation

Related to the Ahlstrom case, Aalto University has been co-operating with Professor Povl Brøndsted at the Technical University of Denmark (DTU) to obtain reference data related to the developed fatigue test methodology.

Applications & impact

FRPs have many benefits when compared to conventional materials. The most important of these are high mechanical performance even in harsh environments, and the potential to make large structures of complex shape with tailored mechanical properties. The results achieved in the FIMECC LIGHT programme considerably increase the knowledge of FRPs and FRP/concrete hybrids, forming a sound basis that enables further development of current products, and paves the way for new cost- and energy-efficient applications.

FIMECC Oy
Åkerlundinkatu 11 A, 33100 Tampere, Finland

FIMECC Factory, Tampere

FIMECC Factory, Turku

FIMECC Factory, Aachen

WWW.FIMECC.COM

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