PRODUCTION TECHNOLOGY WEST

ANNUAL REPORT

2016

UNIVERSITY WEST

ABOUT PRODUCTION TECHNOLOGY WEST

The research activities in production technology at University West is fully organised within the department of Engineering Science, where approximately half of the employees are researchers at Production Technology West, PTW. Professor Per Nylén is head of the research activities with assistance of Dr Lennart Malmsköld, responsible for the research and research education at the department. The research personnel reside at Production Technology Centre (PTC) in Trollhättan with access to modern industrial equipment in cooperation with industry.

The research activities at PTW are organised in three divisions:

- Welding Technology
- Production System
- Subtractive and Additive Manufacturing

The researchers in both the process- and systems oriented fields have access to modern industrial standard manufacturing equipment and skilled operators. The divisions are described in more detail in the following. There are also joint activities where several divsions are involved, e.g. research areas like additive manufacturing or doctoral courses and other skill enhancement initiatives. These are also described in the following.

University West has associated a scientific advisory board to PTW consisting of external expertise:

Professor BENGT-OLOF ELFSTRÖM,
Chairman, GKN Aerospace

Professor UTA KLEMENT,
Chalmers University of Technology

Professor BENGT LENNARTSON,
Chalmers University of Technology

Associate Professor CHARLOTTA JOHNSSON,
Faculty of Engineering, Lund University

Professor JAN-ERIC STÅHL,
Faculty of Engineering, Lund University

Professor MIHAI NICOLESCU, Royal Institute of Technology

Manager Manufacturing Engineering,
HANS WIKSTRAND, Volvo CE

PREFACE FROM THE DIRECTOR OF THE RESEARCH ENVIRONMENT

As always, it is a great pleasure to present the Annual Report summarizing the exciting developments that have taken place at the research environment Production Technology West (PTW) during 2016. Since inception, our mission has always been to undertake and promote cutting edge research in diverse aspects allied to the broad field of production technologies, while keeping in mind the technological needs of the Swedish industry and the concomitant responsibility of the University to develop human resources with requisite academic training. I am delighted that we have made significant contributions on the above front during 2016 to proudly share with you.

In my opinion, the year 2016 was a very successful one by any yardstick. There was an overall increase in the total quantum of research funding as well as a significant rise in publication volume, which are the two key metrics for a research environment. Consistent with the deliberate attempt to augment our research capabilities, I believe we have recruited purposefully to enhance expertise in key areas of welding as well as the emergent field of additive manufacturing (AM). We have also taken important steps to significantly expand our research base in powder-bed AM by acquiring an Arcam A2X system last summer and further augmenting the facilities through establishment of a Gleeble thermal mechanical simulation system. This perfectly complements the already existing infrastructure and expertise at PTW in laser metal deposition, thermal spraying and welding to create a unique environment within the country capable of comprehensively investigating a broad spectrum of prominent AM techniques. I am confident that we are now ideally suited to spearhead a major program on AM in collaboration with strategically identified industrial partners and I look forward to update you on this next year. I am also happy to inform you that, consistent with our growing stature in the field, a Swedish Arena for Additive Manufacturing of Metals was started during 2016, with Swerea, Chalmers and University West as core R&D partners. The arena, intended to be an avenue to enable innovative product development and manufacturing to support R&D in 3D metal printing, is already operational and invites other research organizations and companies to participate.

There were also several pleasing results from all of other PTW areas. Examples in this context are two invited talks (including one Keynote Lecture), two Best Paper awards and initiation of a new fascinating area within thermal spray that relates to luminescent coatings. A General Collaboration Agreement was signed with the European Spallation Source (ESS), Lund for the development of such coatings for high power target imaging systems. I look forward to exciting results to emerge from this cooperation in 2017.

During 2016, as in the past, a conscious effort has also been made by PTW to bolster the competitiveness of industries in the local region. This has been accomplished, for example, through the Maplab project, the 3Dprint project and the 3Dprintplus project. The 3Dprintplus project is being implemented in collaboration with Chalmers and it pleases me that, along with the PROSAM project, this has enabled us to further reinforce our joint research activities with Chalmers. It is extremely satisfying that our collaboration with Luleå University of Technology and Swerea-KIMAB, too, has grown during the year. One example is the Vinnova financed project RobIn (Robust In-process Joint Finding). RobIn is aimed at developing a system to trace the joint in laser welding of a butt joint with a gap close to zero, which is a challenging task.

I am delighted that there is also much to report on the academic front, with several of our students having their licentiate thesis presentations in 2016 - one in machining, three in thermal spraying, two in automation and one in welding. I would specifically like to take this opportunity to congratulate Alireza Javidi-Shirvan, Corinne Charles Murgau and Erik Åstrand who all successfully defended their doctoral theses in 2016.

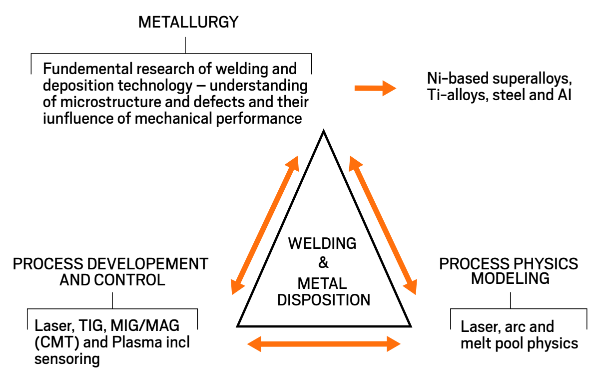
In summary, I would like to thank all our partners - companies, universities, institutes and our sponsors - for their cooperation as well as for the confidence they have placed in us. I look forward to continue our collaborations in 2017! Most importantly, I really wish to thank all the talented employees of the research environment for an impressive job done during 2016 as highlighted in this report. Enjoy reading!

Per Nylén
Head of the research environment
Production Technology West

WELDING

The Division of Welding Technology comprises about 30 people (including senior researchers, PhD students and engineers) and focuses on three main areas in relation to welding technology; Metallurgy, Modelling of Process physics, and Process development and control, see figure below. Welding is traditionally divided into welding process and welding metallurgy and in several academic institutions one of these branches dominates the research. However, to account for the overall picture being of high importance to the welding industry, it is the combination of process and metallurgy which is important. Consequently, the research within the Division of Welding Technology at PTW covers both welding process and welding metallurgy as well as modelling and simulation of the actual heat source and its interaction with the material. The final goal of welding is to realize a product having required mechanical as well as corrosion properties to function in its intended environment. The Division's main objectives are to fundamentally study, understand and improve welding processes and their corresponding influence on the materials and to educate students (master program and PhD students) in the areas of welding and associated technologies. The aim is therefore to increase our knowledge and to perform research on issues and challenges of interest to industry related to welding and associated technologies.

The Division works with most welding processes, but primarily focuses on processes which are common in the industry, such as gas tungsten arc welding, gas metal arc welding, plasma welding, laser welding and friction stir welding. Within welding metallurgy there is extensive activity involving high strength steel, duplex and super duplex stainless steels, nickel-based superalloys, titanium and aluminium alloys. Important properties presently investigated include weldability, corrosion and mechanical properties, especially fatigue properties. The research performed within the Division encompasses experimental studies as well as modelling and simulation studies. It is carried out in collaboration with many international research groups. Simulation of different phenomena relevant to welding, like the behaviour of the electric arc or the light beam from a laser source and their interaction with the material is one of our core areas. In this area, the main activity is Computational Fluid Dynamics simulation of the welding arc and the melt in laser welds. Also, welding is becoming more and more automated and the Division of Welding Technology is closely cooperating with the Division of Production Systems in many topics of industrial relevance as indicated in the bottom left corner of the figure above. The industrial collaboration partners involve both suppliers and end users of welding products in Sweden.



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Partners in joint projects
GKN Aerospace Sweden, Aga, Elga, Esab, Siemens, SSAB, Outokumpu, Volvo, Ytteknik and Uddeholm SSAB, Outokumpu, Volvo, Howden and Uddeholm

HIGHLIGHTS 2016

Discription of the Academic Staff

The Division of Welding Technology has grown since last year and now comprises Joel Andersson (new head of division and Assoc. Prof.), Robert Pederson (new Prof.), Asun Valiente (PhD), Isabelle Choquet (Assoc. Prof.), Americo Scotti (Prof.), Lars-Erik Svensson (Prof.), Leif Karlsson (Prof.), Ingrid Elison, and Sten Wessman (PhD, 20%) from Swerea Kimab.


Robert Pedersson


Johnny K Larsson

There are two full-time welding research engineers within the division, Kjell Hurtig and Mats Högström, as well as four part-time engineers: Kenneth Andersson, Johnny K Larsson (new), Lars-Erik Stridh, and Håkan Backström (new).

There are eight PhD students in the division, five of them in-house (Ebrahim Harati, Vahid Hosseini, Josefine Svenungsson, Tahira Raza, and Andreas Segerstark) and three industrial PhD students (Joachim Steffenburg-Nordenström (GKN Aerospace), Karl Fahlström (Swerea Kimab), and Arbab Rehan (Uddeholm)). We also have four PhD students from Chalmers University of Technology, one PhD student from Luleå University of technology, and one PhD student from University of Manitoba (Winnipeg Canada) that are supervised and co-supervised, respectively, by senior researchers in our division.


Håkan Backström

Progress of Doctoral Degree Students

Alireza Javidi-Shirvan, supervised by Assoc. Prof. Isabelle Choquet, successfully defended his doctoral thesis on the 10th of June with the title "Modelling of cathode-plasma interaction in short high-intensity electric arc - Application to Gas Tungsten Arc Welding". The faculty opponent was Prof. Armelle Vardelle from Limoges University (France). Vahid Hosseini, supervised by Prof. Leif Karlsson defended his licentiate on the 2nd of December with the title "Influence of multiple welding cycles on microstructure and corrosion resistance of a super duplex stainless steel". The discussion leader was Prof. Jan-Olof Nilsson from Sandvik.

Besides these PhD and licentiate theses a number of papers, both journal papers and conference papers have been published by the permanent academic staff and the PhD students. One special event that took place in November was an information meeting on the project "Fatigue properties of welded components in high strength steels". It was a way to inform interested companies about the project on fatigue properties of welded high strength steels that Ebrahim Harati is running.

It can also be noted that Andreas Segerstark spent two months at the University of Manitoba, making advanced microscopy of his additive manufacturing samples and Vahid Hosseini spent five months at the University of Manchester, performing advanced microscopy of his super duplex stainless steel samples. Tahira Raza has been working together with the welding institute in Sheffield, United Kingdom, on preparing selective laser melted samples.

New equipment

A brand new Gleeble 3800D system has been acquired and installed together with a mechanical fatigue testing machine (250 kN Instron Servo-Hydraulic machine), a Varestraint weldability testing machine, a Gantry system for metal deposition and a second-hand scanning electron microscope (SEM) - Zeiss EVO 50 XVP - with significantly improved capabilities compared to the original table-top SEM that has been in our possess for a couple of years.


Gleeble machine


Varestraint machine


Fatigue machine

MACHINING

There is a growing potential in Swedish industry for the area of metal cutting. A large number of Swedish industrial companies, such as manufacturers of mining machinery, heavy vehicles and ball bearings stand strong in the market with new orders and foresee great development in the coming years. New products also require new materials; primarily highstrength steels, lightweight materials and composites. This, in turn, requires better understanding of the relationships between the machine tool characteristics, machining processes parameters, microstructure and component characteristics often including new and challenging hardtomachine materials. The research within machining at University West is, therefore, focused on supporting the industry in meeting these challenges. The area of Machining Dynamics was initiated by Volvo Aero (now GKN Aerospace) in 2006 to establish a research competence at University West. Today we mainly study the processes of drilling, turning and milling with focus on dynamics in drilling operation and frequency domain identification and optimization of milling systems. Research on drilling processes, has the longest history in the group and was initially focused on design of highfeed drill geometries for difficult tocutmaterials. This area for research was widened later and research on cooling technology, temperature measurement and numerical modeling of cooling and chip formation has been added. These studies create a deeper physical understanding of the machining process including what happens to the workpiece and the tool as a consequence of machining. A central area of interest is data analysis and signal processing to gather information about the vibrations, tool wear and surface quality of the machined part. This information can for instance be used for selection of high productivity cutting conditions. The knowledge of how vibrations are avoided even at large feeding speed and cutting depth has a significant impact on productivity. The area of Machining Process and Surface Integrity focuses on the machining parameters that influence the final product characteristics while cutting conditions are selected to manufacture the component in the shortest time possible and at the lowest cost. The area of Process Planning and Monitoring of Machining Processes focuses on procurement strategies to optimize profitability of machine tools, including product life cycles and maintenance costs. To facilitate this, all gathered knowledge about the processes is applied in a decision support system that provides predictable and reliable results of factors influencing the outcome in a transparent manner. Tool wear models are integrated in CAM systems to facilitate maximizing the life of cutting tools.

National and International collaboration

Academic collaboration is currently ongoing with University of British Columbia, (Canada), the Norwegian University of Science and Technology, Chalmers, Swerea and Örebro University.

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Partners in joint projects
Sandvik Coromant, SECO Tools, Uddeholm, Brogren Industries, GKN Aerospace, Swerea Kimab, Swerea IVF, Scania

HIGHLIGHTS 2016

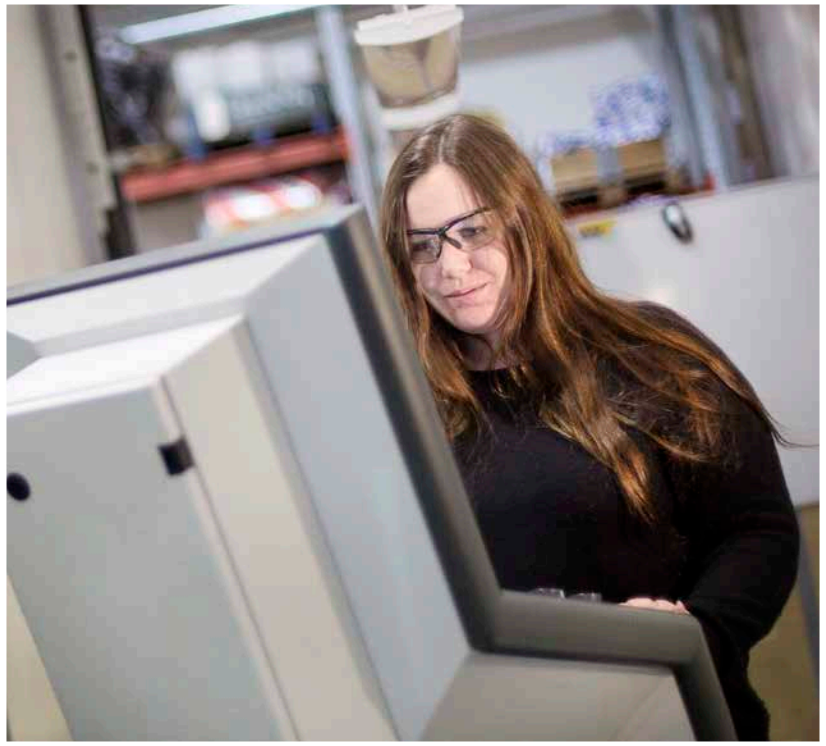
Vibration in machining

The IOOI project investigates the vibration frequency relationships in machining to calculate the dynamic parameters of a machine tool during its operation. These parameters are important in selection of parameters of robust machining operations that avoid chatter vibrations that can leave an irregular surface finish on the workpiece.

The project has started in 2016 and until now, algorithms are developed for extraction of parameters when a single mode of vibration is causing chatter. The vibration frequency relationships are extracted when single and coupled modes of spindle and tool involve in chatter. Furthermore, a new algorithm combines multiple measurements to increase the precision of extracted dynamic parameters.

Ongoing efforts are focused on handling more complex machining structures where multiple modes interact and influence emitted vibration frequencies.

Surface after machining at 7875 rev/min, 4,5 mm depth of cut.

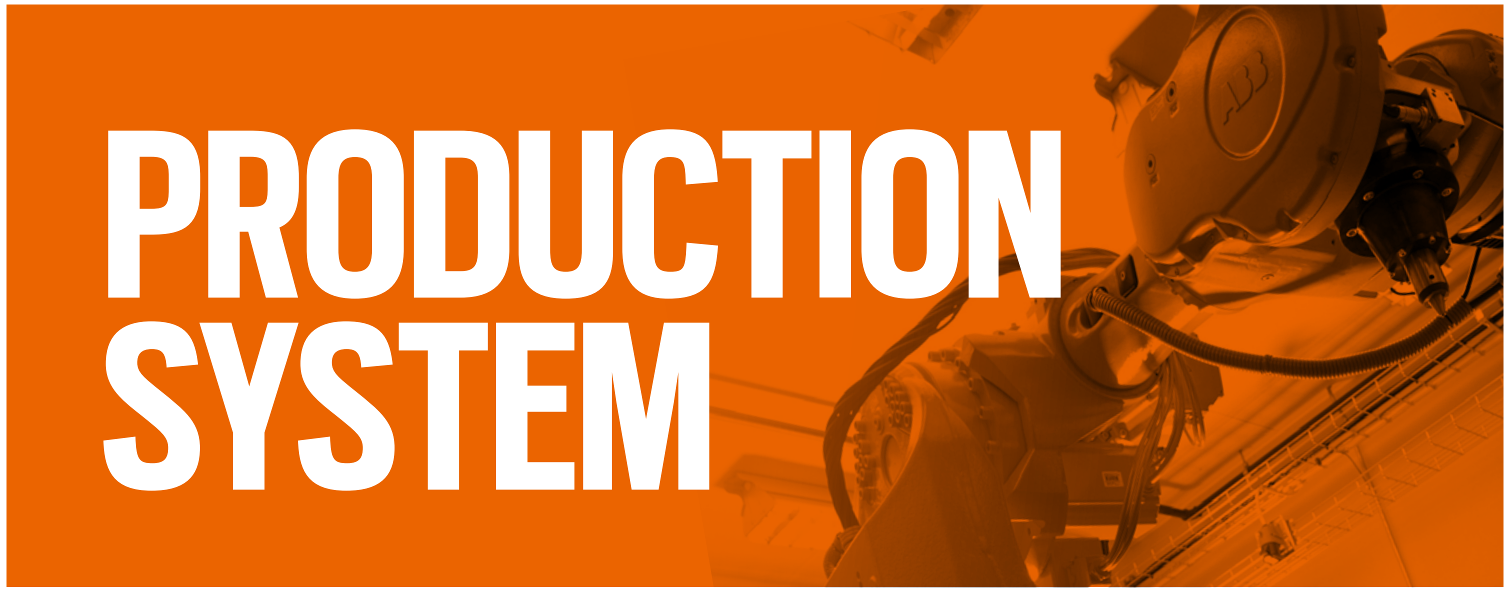


Machining process monitoring research

During 2016, several machining experiments were conducted to extend the developed monitoring methodology based on internal sensor signals and apply it to continuous maching operations, such as phase turning. The research was focused on the detectability of tool wear under relatively harsh industrial conditions. The main findings from these activities were that a multi-axis measurement approach is necessary to capture the dynamics of the machining process. Also, by focusing the analysis efforts to a specific frequency band and evaluating the displacement ratios in the radial and tangential directions, the event of tool chipping could possibly be indicated in a statistical process control chart (SPC). Further work is however necessary to solve the real-time monitoring issues related to machining process monitoring.

Best poster award

Best poster presentation award for the Paper "EDS Analysis of Flank Wear and Surface Integrity in Machining of Alloy 718 with Forced Coolant Application" by H. Jäger, N. Tamil Alagan, J. Holmberg, T. Beno and A. Wretland at 3rd CIRP Conference on Surface Integrity, CSI 2016 at Charlotte, North Carolina, USA.



PRODUCTION SYSTEM

Production Systems (PS) comprises two main research areas, Robotics & Automation, and Control & Inspection. Within PS a master in Robotics and Automation has been developed and will be launched in 2017. At large, PS is about how production systems should be configured and operate in an efficient manner. It also includes sub sets of such systems, which can be exemplified by humans, robots, machine tools and various IT systems as embedded systems controlling processes, sensors and information infrastructure. On the detailed level, the Division has specific research challenges related to control of production processes, inspection methods and related data analysis, which concerns quality and data for controlling processes, configuration of production systems with optimization issues, simulation, programming and commissioning, safety issues, and human issues, which can include collaboration and Human Machine Interfaces (HMI).

The research in Robotics & Automation is directed towards flexible, reconfigurable systems and autonomous operation within a robot cell or smaller robot systems comprising a limited number of robots and machines, autonomous agents. Within this area automatic code generation is in focus as well as collaboration operator – robot where issues such as task sharing, interfaces and sensor systems are in focus.

For Control & Inspection the research has had an emphasis on model based concepts related to in-process control and monitoring. Examples of applications for this area are different welding processes and additive manufacturing which connects to researchers at other groups at PTW. Inspection include sensor systems and data analysis that relate to identification and classification of actions to be taken concerning further processing of a product, such as in-process control or post control and inspection. Specifically, thermographic method is an area for research which has promising results as a non-destructive method.

Both research areas described above target common challenges related to the trend towards mass customization and Industry 4.0. Manufacturing should be highly flexible and based on autonomous systems, often localized controllers, which can communicate within an information infrastructure. Furthermore, methods need to be developed that can be applied to processing and manufacture of a product during several stages, within the context of a model based approach. A model based approach makes it possible to adapt different processes which include monitoring, control, inspection and system configuration, in accordance with specification for the product. Moreover, in-process monitoring and control create opportunities to adapt and alter subsequent process stages for the product to be aligned with defined specifications. Thus, future systems in manufacturing including control and inspection must be highly flexible and adaptable, and be able to react on changes during processing and production of a product. In summary, the research areas represent core subjects within production systems in general and they represent important areas of both research and education within PS.

During recent years, research and education within PS has evolved in many ways. The number of professors has grown with three more during 2016, and PS is well integrated into the PhD program Production Technology with a PhD dissertation as well as two Licentiate Thesis during 2016. This is expected to be an important part of PS in many ways; it will provide future candidates for PhD studies, it will be a platform for exchange of students and academic networks as well as full semester degree projects. Such degree projects can take place within such network as well as in industry, and complement researchers with valuable teaching and meeting students in relevant subjects.

Core areas within Production Systems and important relations are displayed in Figure 1 with subjects related to respective area.

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Partners in joint projects:
Binar, Brogrens, GKN Aerospace, Innovatum, Lamera, Lortek, Permanova, Scania, Siemens, Swegon, Swerea Kimab, Teknitesh, Termisk systemteknik, TWI, Volvo Cars and Volvo CE

HIGHLIGHTS 2016

In-process Control and Monitoring

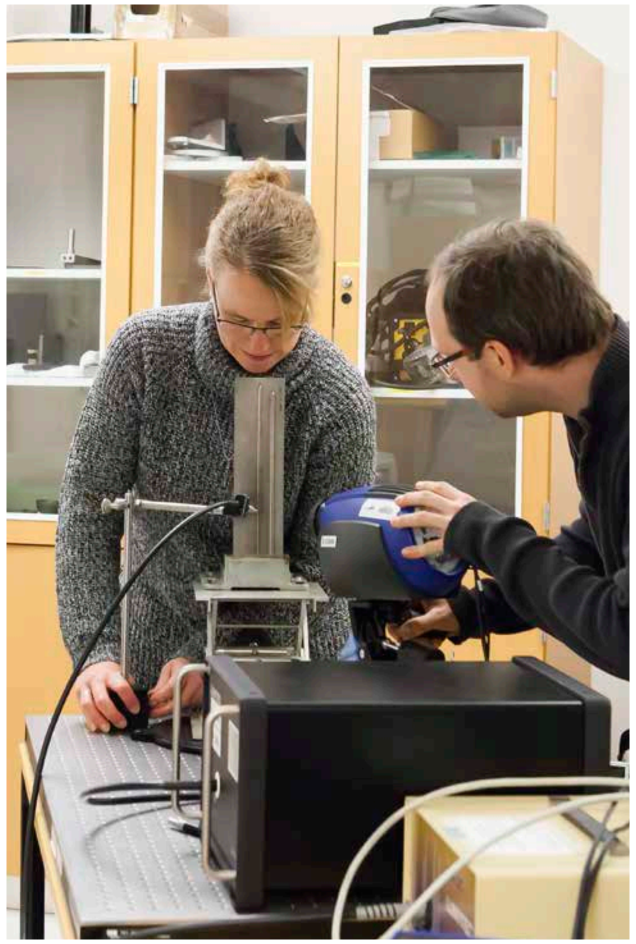
A strategic cooperation amongst University West, Luleå University of Technology and Swerea-KIMAB and key industrial partners was initiated by the Vinnova financed project Robln (Robust in-process joint finding). Robln aimed at developing a system to trace the joint in laser welding of a butt joint with a gap close to zero. In industry, there is currently a lack for such systems with enough accuracy and reliability. The suggested answer is a camera based system that analyzes certain wavelengths in the visible range of the LED illuminated joint area in combination with a laser line scanning sensor. The signals are treated and algorithms have been created to identify the position of the joint relative the laser beam spot. The system was tried for different materials such as nickel- and titanium alloys as well as stainless steel in a specially designed demonstrator. It was tested with varying butt joint gaps down to technically zero gaps, scratches resembling the joint located very close to the joint, tack welds covering the joint and with a non-linear joint path. The system has been successfully tested off-line and the joint can be identified and separated from, for instance, scratches. Further development is yet needed to be able to display a fully adaptive control system. The Laser Group R&D (Lasergrupp FoU), a forum for discussing the need of research and development in the laser welding industry has been formed from the Robln frame work.

Robln has been up followed by the Vinnova financed project VarGa (Adaptive Control of Varying Joint Gap in LBW). VarGa aims at developing an in-process solution in order to secure a uniform weld joint geometry and weld properties despite the presence of joint gap variations and uncertainties in joint position. Starting from the Robln project´s results, with the objective to use varying filler wire and close the loop in the control, the in-process system will be based on a nonintrusive vision sensors system together with special illumination integrated in the laser beam welding tool combined with suitable in-process control of the filler-wire feed-rate, welding parameters and robot path corrections.

Automated Non-Destructive Testing (NDT) and Inspection

This project´s goal was to make it possible to inspect weld in hard-to-reach areas. The result of the 18-WeLdt, a joint research project, including University West, GKN Aerospace in Sweden, Tecnitest Ingenieros and IK4 Lortek in Spain, is a demonstrator based on a thermography system with an infrared thermal camera and excitation by a continuous laser line, in combination with a borescope for both the excitation and the viewing. The entire system is set on a robot arm, making it possible to automatic scan hard-to-reach areas. The need on cut fuel consumption in aero engines, where reduced weight is a possible solution, required this. A risk with lighter structures is reduced margin of safety. One step to solve that problem is better quality control in production and regular maintenance inspection. With an increased need of inspection there is a demand on automation solutions. The design of the aero engines of tomorrow is a challenge, when it comes to inspection due to the location of the welds in hard-to-reach areas. This requires new methods for inspection.

The NDT methods that have been used in the 18-WeLdt project is thermography. The principle for that way is to introduce a controlled heating of the surface (excitation) and register the heating and cooling sequence by an infrared thermal camera. Thermography is a non-contact and full field method, which makes it suitable for automation.



Dr Anna Runnemalm and Dr Patrik Broberg, NDT-reseachers.

Welding procedures

While welding has been used for about 100 years, and the technology has evolved considerably, the weld is still often a weak link in a design. This particularly applies to structures subjected to rapidly varying loads, so-called fatigue. Samples are in particular vehicles of various types. To develop more environmentally friendly vehicles, you need to use steel with increasing strength and which also weigh less. Unfortunately, the welds limited fatigue strength often limit the ability to use high strength steels.

In a thesis, by Erik Åstrand at University West, he tells how the manufacture of welded structures subject to fatigue can be improved in the future. The premise is that a good weld can create added value by offering a lower cost, longer life and higher load capacity. Erik Åstrand has examined how by varying the welding necessities and welding procedures based on load case, for the weld can get a better result.

A vital conclusion regarding custom welding procedures and related requirements relate to prioritize what is important and to prioritize off what is not important. It is difficult to produce welds having good properties all-round. In theory, it is often fairly simple changes, but in practice, it is challenging to implement. The results show that the welding standards and quality levels need to be updated as well as the design rules, as they are not suited for welding with a high fatigue strength. A major challenge is to implement a new approach where welds are specified and produced with the new requirements and different levels of quality.

Sweden Robot Hack

Sweden Robot Hack, a thrilling event with a big audience, took place in November. 9 teams from West Sweden raced in making the most innovative program to challenges the task in building a tower, according to sharp rules. The teams involved university-students and one team from a high school. The programming was made in a purposed design API that generated RAPID code for the ABB robots as well as simulation of the code in Robot Studio. All teams had to demonstrate the final results on real industrial robots from ABB Robotics

Digitalization and Industry 4.0

Digitalization and Industry 4.0 is on the agenda in production systems, a hot topic that has been included in many activities during the year and we expect several projects and events will cover this area in the coming years. Project Miljo:FIA, submitted in 2016, focuses this topic in the scope of highly flexible and reconfigurable robotic systems and flexible solutions on reconfiguration will be tackled, as well as safety in collaborative systems. In the concept of collaboration, Human Machine Interfaces are included. Another project, Digit-AM (faster introduction of additive manufacturing through digitalized quality assurance and digitalized products on shelf stock) started and continues through 2017.

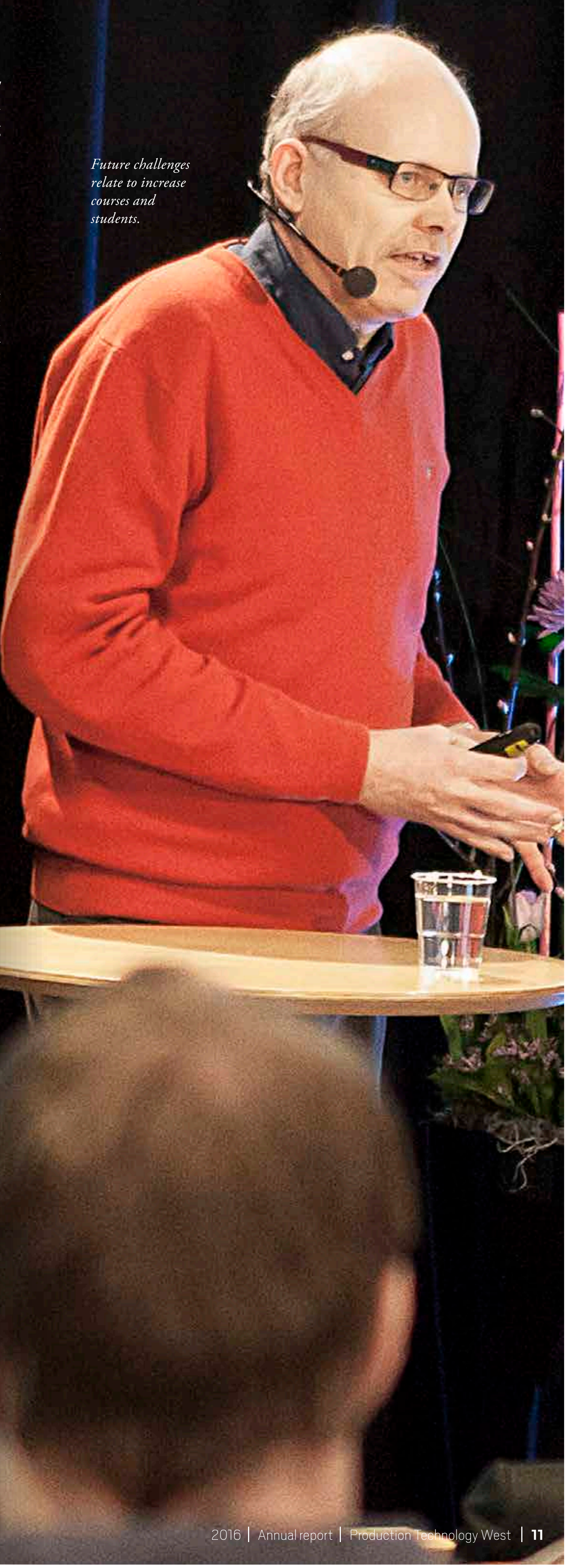
Gunnar Bolmsjö, professor of robotics at University West held several lectures covering this during the year; on Researcher night, theme "Digitalisation and robotization of society", at the event "Fika med forskare" and at an open lecture on the topic "Industry 4.0". Bolmsjö also contributed during a workshop on "Digitization and automation in the Nordic manufacturing sector", financed by the Nordic Council of Ministers, held in Copenhagen.

ProdEx – Expert in Production Technology

In the scope of developing methods and tools for transferring knowledge and competence between academia and industry, two project are ongoing. VALUE - within the program "IT i Högre Utbildning"/"IT in Higher Education" focuses on developing IT infrastructure and digitalization of exercise and laboratories. The other on collaborative support together with industry in competence on advanced level - ProdEx - within the program "Expertkompetens för Innovation"/"Expert competence for innovation". Prodex 2 (phase 2) started with a kick off in September. A great educational project funded by the Knowledge foundation. In April, we got 10 million to develop courses in production technology at the advanced level of the industry (170 participants). Corporate representatives were present at the kick-off/presentation of the project and its objectives as well as an insight in the technology and equipment used in the courses exercises and an insight in the latest in automation research. A joint discussion of courses and co-production forms ended the meeting. Co-production is an essential condition for the project.

Main activities in the projects are to form collaboration with industry and investigate current and future needs for knowledge. Based on this, short-courses are developed and offered. During 2016 shorter-courses have been given in automation, calculations with Matlab, simulations using LS Dyna, metal cutting, robotics and production management. Methods developed alongside IT infrastructure and ICT tools in order to facilitate for efficient course classrooms in mixed mode, physical in real life and Internet based learning environment. Appropriate form of courses are 2,5 credits/course, given one day a week over a five week period. In addition, methods to convey course content using digital media has been tried, developed and worked with for the pilot courses. This is an ongoing work that will continue 2017.

The experience is that short-courses at advanced level are needed, providing efficient knowledge transfer and giving participants, as well as industries, benefit of knowledge, ahead of competitors. Putting them in a better position with more openings to manage challenges, today and tomorrow. Future challenges relate to increase courses and students, and develop methods to virtualize advanced lab units and exercises. New short-courses will be made and offered and new content will be introduced based on the needs from industry. These include, but are not limited to, robotics, safety and risk analysis in production systems, various CAX software tools, and applied solid mechanics using tools like FE simulations and more.



Future challenges relate to increase courses and students.

ADDITIVE MANUFACTURING

The team at University West has vast experience (>10years) in metal wire additive manufacturing (AM), powder deposition by laser and thermal spraying, as well as laser and electron beam processing in general, with about 200 publications between them. University West is also considered to be among the top groups globally in robotized laser wire AM. Although University West's foray into AM technologies based on powder-bed methods is only recent, it ideally complements the significant existing expertise in Laser Metal Deposition (powder and wire), thermal spraying and welding to create a unique environment. The above expertise and availability of associated facilities, was in 2016 further augmented by an Arcam A2X system and Gleeble thermal mechanical simulation system which also installed in 2016, makes University West ideally suited to spearhead efforts in the AM area. Consciously, the AM research at University West is not performed (and neither planned to be) within a single specific division in the research environment; instead, a multi-disciplinary research team comprising researchers from all three divisions within PTW is involved in the ongoing efforts to investigate varied aspects of AM. The team has grown significantly in recent times with one professor, two visiting professors, one adjunct associate professor, and four PhD students being recruited during 2016 alone.

International collaborations

Three international research environments have been identified for prioritized partnerships namely Oak Ridge National Laboratory, Sheffield University, and Cranfield University. The expertise existing in these groups ideally complements the strengths at University West to enable synergistic partnerships that can accelerate research output in various AM-related focus areas being addressed at HV.

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Partners in joint projects
Siemens Turbomachinery, GKN Aerospace Engine Systems, Exova Materials Technology, Quintus Technologies, Innovatum, Brogrens Industries, Sandvik Materials Technology, Arcam, Permanova Lasersystem, Swerea Kimab, Swerea IVF

HIGHLIGHTS 2016

The research efforts within Electron Beam Melting (EBM) were significantly ramped-up in 2016. EBM is a rapid scanning process, which produces parts like any other AM technique in layer after layer fashion, but the rapid solidification of thin layers gives rise to issues such as directional grain growth, anisotropy, inhomogeneity (micro segregation of chemical composition etc). Therefore, several research efforts were initiated:

Research was initiated to provide the necessary understanding of relationships between critical process parameters, microstructure and mechanical properties of as-fabricated Inconel 718 parts. Focus is placed on design of an optimized as-fabricated microstructure especially δ phase distribution.

There is a need for post treatment of the EBM-parts to meet the requirements of the working conditions. Research was therefore initiated to gain fundamental understanding of the effect of post treatment parameters such as temperature, time, and pressure on the microstructure of the processed Inconel 718 material. The effect of heat treatment and HIP parameters (temperature, time, pressure) on the grain structure, porosity, and phases: γ', γ'', δ, NbC is here of specific interest.

Work was also initiated on developing models that can capture the relationship between microstructure characteristics and corresponding mechanical behavior of EBM manufactured Inconel 718. Microstructure images (EBSD) is used as an input and models developed to predict the mechanical behavior. To validate the models, experiments including acoustic techniques and tensile testing were evaluated.

There are six PhD students within AM: Tahira Raza, Andreas Segerstark, Paria Karimi Neghlani, Chamara Kumara, Arun Ramanathan Balachandramurthi and Sneha Goel

THERMAL SPRAYING

Thermal spraying (TS) was the first area in which research activities were initiated at University West. The research group is now mature and poised to expand its research base. The group's research activities have spanned varied aspects including process development, on-line diagnostics, characterization of microstructure, determination of thermo-mechanical properties, assessment of coating performance in simulated environments and investigation of failure mechanisms. The initial research focus was dominated by development of coatings for thermal insulation, so-called thermal barrier coatings (TBCs), for gas turbine applications. The foundation laid in the course of meeting the extremely stringent specifications demanded by TBCs has enabled the research group to extend its expertise during the past ten years to developing coatings for solid oxide fuel cells (SOFCs), for wear resistance, and more recently for corrosion protection. In recent years, specific attention has been paid to exploring new thermal spray processes that can create novel coating microstructures. Particularly noteworthy are examples of suspension plasma spraying (SPS) that enables spraying with nano/submicron feedstock to create novel TBC coatings with columnar microstructures, and high velocity air fuel (HVAF) spraying that permits deposition of very dense coatings for superior wear and corrosion resistance. The enhanced process understanding is also being utilized to explore deposition of powder-suspension hybrid coatings to generate function-dependent coating architectures.

The above activities are consistent with the group's vision to establish University West as one of the world leaders in the field of TBCs, while also creating an internationally recognized research group in the areas of high-temperature corrosion and wear-resistant coatings. The group has progressed significantly in this direction. New research programs on heat insulating TBCs for gas-turbine and automotive applications, as well as on development of coatings for corrosion protection at high temperatures in boiler plants, have been recently initiated. A promising beginning in the field of luminescent coatings has also been made.

The TS research is performed within the Division for Subtractive and Additive Manufacturing. The TS group currently (2016) consists of two professors, one associate professor, two lecturers, two engineers and three academic PhD students. The group's capabilities are further augmented by the close research relationships established with leading international universities and institutes that pursue thermal spray research. Prominent examples of such collaboration partners are Forschungszentrum Jülich (Germany), Fraunhofer Institute (Dresden, Germany), Stony Brook University (USA), Manchester University (UK), University of Nottingham (UK), Tampere University of Technology (Finland), University of West Bohemia (Czech Republic), Institute of Plasma Physics (Czech Republic) and University of Modena (Italy). Strong mutually rewarding linkages have also been established with national research partners, mainly with Chalmers University of Technology, Uppsala University, Linköping University, and Jönköping University.

FACTS

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Senior researchers
Prof. Shrikant Joshi, Prof. Per Nylen, Assoc. Prof. Nicolaie Markocsan, Dr Mohit Gupta, Dr Christophe Lyphout and Engineers Stefan Björklund and Jonas Olsson.

Partners in joint projects:
GKN Aerospace Sweden, Aga, Siemens Turbomachinary AB, Höganäs AB, ABB Force measurements AB, Oerlikon Metco, Treibacher AG, Innovnano, H.C. Starck, Volvo Cars, Scania, Volvo Trucks, Sandvik Heating Technology AB, Valmet, MH Engineering, Trollhättan Energi, BillerudKorsnäs Skärblacka (BS), Borås Energi och Miljö (BEM).

HIGHLIGHTS 2016

Research on heat insulating TBCs for gas-turbines and coatings for has been ongoing 2016. Suspension spraying was shown to be a promising route for further advancement of Thermal barrier coatings. The SPS process also was shown promising as a coating method for solid oxide fuel cells (SOFCs) within a three-year KK foundation funded project that ended in December 2016. University West was the first in Sweden to build up a cell by thermal spraying and achieved good electrochemical test results. Activities in new application areas were also initiated in 2016. Examples in this context are thin hydroxyapatite biocompatible coatings with high crystallinity, good adhesion and low porosity, attractive for implants and other surgical products, produced by SPS as well as titania coatings with photocatalytic properties produced with the same technique.

Offshore, wind energy, energy generation from waste and biomass automotive are some examples of applications where corrosion is a major concern. Research was in 2016 was also conducted on developing coating systems for improved wear, erosion and corrosion resistance at low and high temperature. Research on high temperature corrosion protective coatings for power plant boilers was initiated autumn 2016, jointly with Chalmers University of Technology. In order to further expand the utility of the SPS technique, the group has also successfully shown that sequential and simultaneous feeding of hybrid powder-suspension feedstock can be gainfully active to get function-dependent layered, composite and graded coatings. Another appealing area has emerged during 2016 and relates to luminescent coatings. A General Collaboration Agreement has been signed with the European Spallation Source (ESS), Lund for the development of such coatings for high power target imaging systems. Different material systems such as Al_2O_3, Al_2O_3: Cr_2O_3 and Y_2O_3 have been initially explored, with the Al_2O_3:Cr_2O_3 coatings already yielding promising results. Further tests at CERN, GSI, Oslo University, COSY, and BLIP are rolling.

Best paper awards

- "Deposition of Novel Composite Coatings by Suspension-Powder Hybrid Plasma Spraying" by S. Goel, S. Björklund and S. Joshi, at the 7th Swedish Production Symposium SPS16, Lund October, 2016.
- "Hot corrosion behavior of multi-layer suspension plasma sprayed $Gd_2Zr_2O_7$ /YSZ thermal barrier coatings", by K. P. Jonnalagadda, S. Mahade, N.Curry, X-H. Li, N. Markocsan, P. Nylén, S. Björklund, R. L. Peng, at the International Thermal Spray Conference ITSC 2016, Shanghai, China May, 2016.

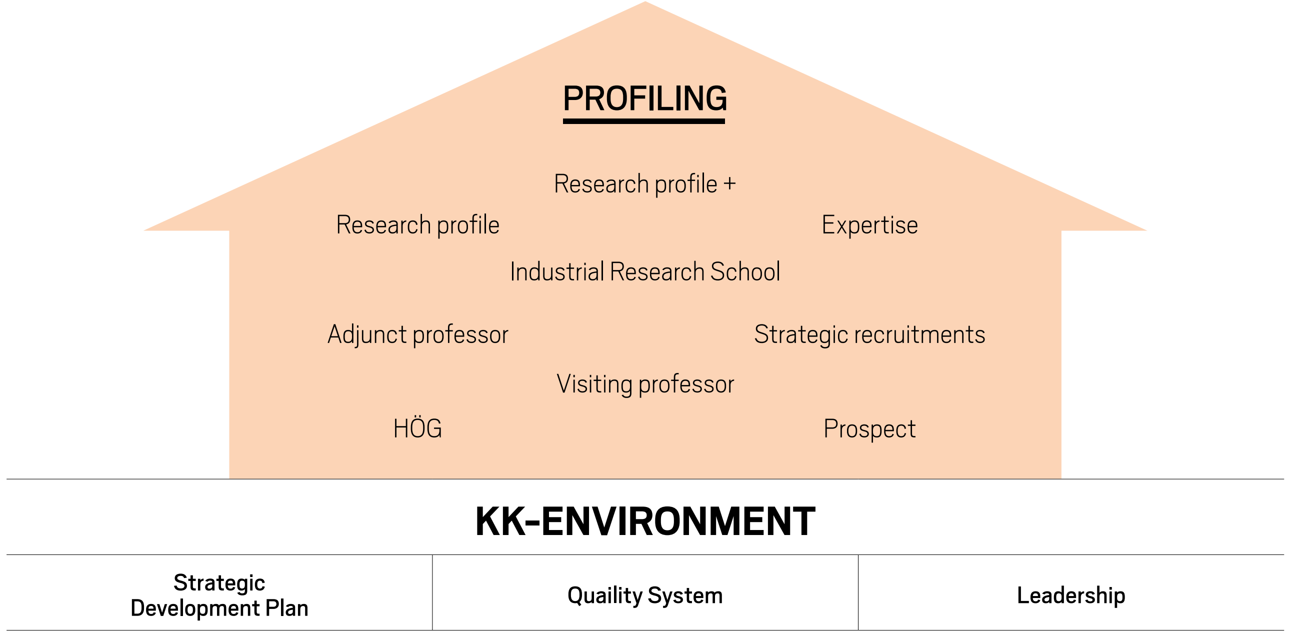
SPS summer school

With its leadership position in the field, the group organized a Summer School on "Suspension & Solution Thermal Spraying" during September, 2016. The widely attended School included lectures by experts from academia and industry covering diverse aspects of liquid feedstock spraying, as well as a demonstration of the state-of-the-art suspension plasma spraying equipment.

Invited talks

S. Joshi delivered a keynote lecture on "Hybrid Plasma Spraying Using Powder and Solution Feedstock: A Promising Pathway to Realize Diverse Coating Architectures" at the Turbine Forum 2016 International Conference on Advanced Coatings for High Temperatures, April, 2016 in Nice, France.

N. Markocsan delivered an invited talk on "Functional coatings for high temperature applications in transport and energy sectors" at the Symposium on Advanced Thermal Spray Coatings for Energy and Transportation Applications, May, 2016 in Shanghai, China



TOWARDS A KK-ENVIRONMENT

PTW has during the last 6 years been successful in receiving funding for several large projects. Many of them have been funded by the Knowledge Foundation (KKS) and due to the good track record of funding from KKS over the past five years, KKS invited University West in 2015 to start preparatory work for qualifying the university's research environment for funding from KKS under the "KK-environment" program. This opportunity is only offered to universities that are recognized as potential candidates for excellence by KKS, and once qualified for a KK-environment there is no open call from KKS for those within the KK-environment. The idea of the ten year long KK-environment program is to support strategic development and profiling of the university. It is a tool for facilitating continuous improvement in research capabilities and propel the university towards a leading position in research and knowledge development within areas selected by the university. The areas will profile the university, and the KK-environment will also develop the university's ability to forge strategic collaboration and co-production with companies in Sweden. The long term objective of the KK environment program is that the university that qualifies for the program will develop into a clearly profiled and research intensive university, with a strong and viable research and training activities based on co-production within clearly defined profile/profiles. A further objective is that the university will be recognized for excellence in its selected areas, and can thereby attract an increasing proportion of external funding, also from other research funding organizations. The university should, through the established KK-environment, also be more successful in recruiting eminent researchers and talented students and to be an attractive partner for companies that the university defines as being strategically crucial. Finally, an objective is also for the university to attain a stable and recognized position in the Swedish and, by the end of the program, also in the European university sector. The planned KK-environment at University West will initially include all existing research areas within PTW and, in addition, Industrial Work Integrated Learning, which will be a collaboration with another research environment at University West named LINA (Learning in and for the New Working Life). During 2016 the work towards a KK environment has accelerated. Several recruitments, mainly professors, have further strengthen the competence in PTW and the intended new KK environment. Other activities that could be mentioned are: A common work with all involved research groups have given a solid strategic plan for how the research should be developed in the environment, the quality assurance system has been developed and tested in several loops, a larger project has been developed for the grand piloting of the quality assurance system and the management organization for the planned environment has established its work. The final parts in the development and qualification phase, where the review and the final decision from KK will be taken, are expected in spring and early autumn 2017. The environment is planned to start in January 2018.


Lennart Malmsköld.

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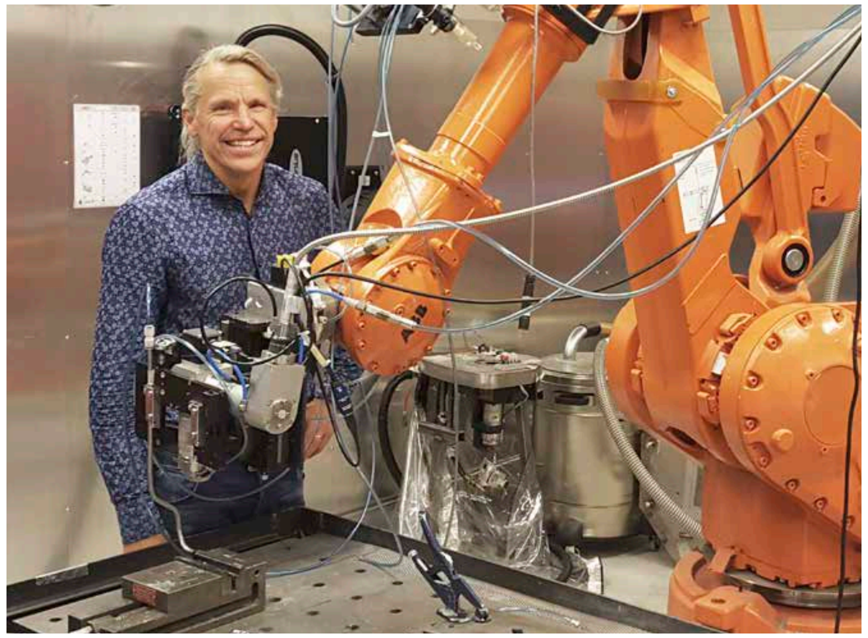
SUMAN

SUSTAINABLE MANUFACTURING PROCESSES



The six-year project "SUMAN" (Sustainable Manufacturing Processes), funded by the KK Foundation, University West and the industry, will culminate in February 2017. The project has involved advanced research focusing on various facets of Production Technology in close cooperation with the University's strategic industrial partners. The aim has been to conduct internationally competitive research in the broad domains of welding, thermal spraying and automation, with the intention of developing manufacturing processes and products on the cutting edge.

Some examples of research under SUMAN have included developing new manufacturing methods for aircraft components, exploring new types of fuel cells and creating new methods relevant to additive manufacturing. Given the interdisciplinary nature of the various work packages associated with the project, which are at the interface between materials, production, and measurement/control technologies, collaboration between the three divisions at PTW has been central to the success of SUMAN. In the course of its implementation, a strategic long-term research environment, with further expanded expertise of all senior researchers involved, has been established. This has not only significantly strengthened and profiled the university, but also laid the foundation for creating niche expertise for continued research for industrial benefit. This is wholly consistent with the University's aspiration to become an internationally competitive research environment, while improving Sweden's competitiveness as an industrial nation.

MAPLAB

SUSTAINABLE PRODUCTION THROUGH LABORATORIES FOR MATERIAL CHARACTERIZATION

The Maplab project aims to strengthen innovation processes, skills and knowledge in sustainable production in manufacturing companies in the region. The project consists of four parts: (i) fill a gap in the laboratory environment equipment facilities in materials and property testing to process control and evaluate material properties and also significantly enhance the environment with experienced researchers; (ii) Establish a cost-effective, functional interaction structure between our research groups and other national research groups and companies in the region, (iii) Establish long-term, international research collaborations with world-leading research environments in such a way that it significantly strengthens the region's manufacturing industry, including SMEs, (iv) Utilization of research results is a horizontal, integrated part of other projects running.

Six research projects within MAPLAB have been initiated during 2016:

- Process development in arc welding
- Additive manufacturing using laser metal deposition,
- High temperature corrosion coatings for environmentally friendly energy,
- High Temperature Coatings for environmentally friendly gas turbines
- Robotic Friction Stir Welding (FSW), and (vi) Fatigue of welded structures, very high strength steels.

During 2016, equipment related to these sub projects have been procured and installed and demonstrators and tests have been initiated. The project continues throughout 2017.

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PROSAM – CHALMERS & PTW COLLABORATION

The PROSAM project has been financed by Västra Götalands Regionen (VGR) during 2014-2015 and got, in beginning of 2016, an approval for a second phase with end in December 2017. The second phase will continue the work in strategic collaboration of research efforts within production technology between University West (PTW) and Chalmers aiming for appropriate business oriented research leading to strong international competitiveness.

In the second phase the selected areas span Automation, Machining, Quality Assured Welded Structures, and Thermal Spray. In the Thermal Spray area new collaboration has started with non-organic chemistry which makes the thermal spray group involved in two different collaboration areas with Chalmers.

Main activities in the respective areas have been

- Joint research plans for PTW and Chalmers research teams
- Execution of joint research
- Joint applications for funding of collaborative research programs
- Development of academic and industrial research networks

Within the selected research areas, the following results have been achieved as a result of PROSAM:

INDICATOR/TARGET	Goal (after 2+2 years)	Status (after 2 years)
New R&D networks	4	6
Joint scientific publications	20	12
New joint national research applications (most in cooperation with regional industry)	3	7
New joint international research applications	3	1
Companies involved in research projects	8	10
Degrees	14	3
Additional scientific publications *(University West-portion)	30	32*

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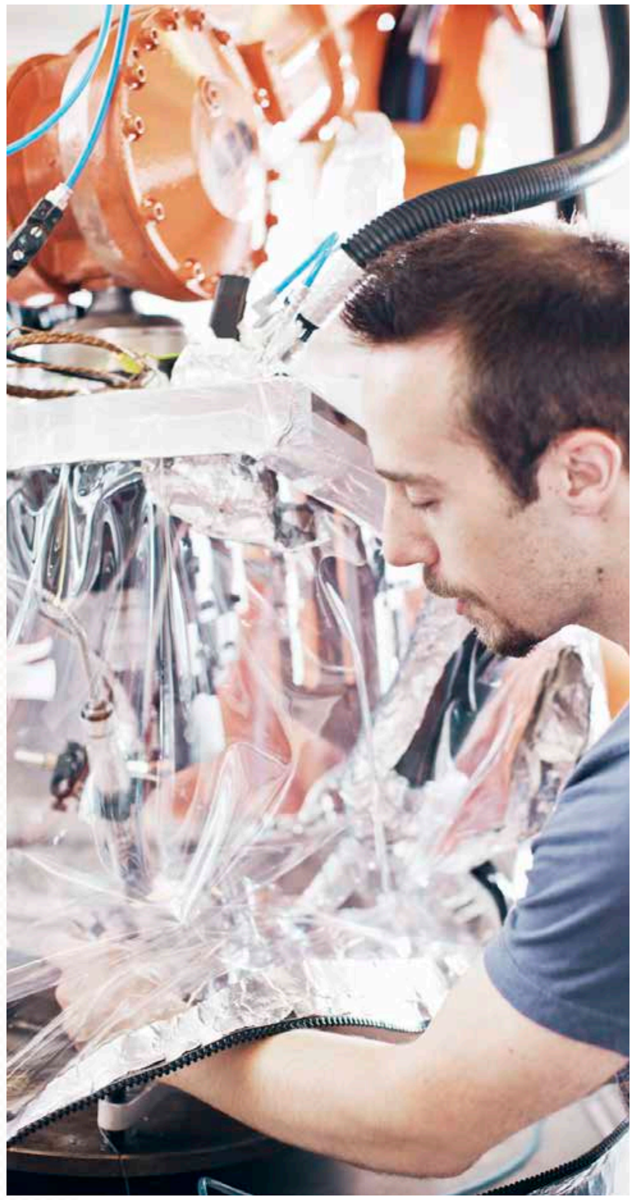
The Phd students involved in PROSAM are (from left): Nageswaran Tamil Alagan, Emile Glorieux, Ashish Ganvir och Esmaeil Sadeghimeresht.



INNOVATION AND UTILIZATION

Knowledge becomes utilization An innovation may be defined as something new that ”breaks into” the market or society. Several activities have been performed during the year to increase utilization of research results, and to contribute to the dissemination of results. When a potential for utilization could be identified, specific verification projects have been started. One example is the project “Optimization of cutting tool utilization”.

Optimization of cutting tool utilization

The search for increased productivity and cost reduction in machining can be interpreted as the desire to maximize the material removal rate, MRR, maximize the cutting tool utilization, UTL, and minimize the machining cost, Cm. The MRR is defined as a function of three variables: the cutting speed, the feed and the depth of cut, which all constitute the cutting data. Tool life is the amount of time that a cutting tool can be used and is mainly dependent on the same variables. Two different combinations of cutting data might provide the same MRR, however the tool life and machining cost will be different. Thereby the selection of the cutting data needs to be done as the balance between the maximal MRR, maximal UTL and minimal Cm.

An integrated optimization algorithm for cutting data selection based on maximal MRR, maximal UTL and minimal Cm has been developed. The algorithm allows the Process Planner or CAM Programmer to visually understand the relationship between the cutting data selected and both MRR, UTL and Cm. Further, the developed algorithm shortens the time dedicated to the optimized cutting data selection and the needed iterations along the program development. Therefore, the selection of cutting data parameters can be oriented towards productivity and better planning of the CNC-program.

DOCTORAL DEGREE PROGRAMME

Since 2012 University West offers a doctoral degree programme in Production Technology. A doctoral degree programme comprises 240 university credits, equivalent to four years of full-time studies. The programme consists of a research project and a number of courses determined by the research subject. Research results are reported in journal and conference papers and finally compiled in a doctoral thesis which is to be publicly defended. Normally, a licentiate degree is issued half way after a licentiate thesis is presented.

PTW also runs a KK-funded project "VALUE - Virtualization of Advanced Lab Units and Exercises" for developing doctoral courses at a distance, which will facilitate increased participation of PhD-students from other universities.

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Director of Doctoral Studies: Associate Professor Maria Skyvell Nilsson, maria.skyvell-nilsson@hv.se

ALIREZA JAVIDI -SHIRVAN
(CHALMERS), Ph D 2016
Modelling of cathode-plasma interaction in short high intensity electric arc – Application to Gas Tungsten Arc Welding

ANA MAGALHÃES
Lic 2016
Process automation of FSW from both an academic and industrial perspective

ANDREAS SEGERSTARK
Influence of Laser Metal Deposition Process Parameters on Microstructural Characteristics

CORINNE CHARLES MURGAU
(LTU), Ph D 2016
Constructive Cooperative Coevolution for Optimising Interacting Production Stations

EBRAHIM HARATI
Fatigue strength of welds in high strength steels- Effects of weld toe geometry and residual stress

EMILE GLORIEUX
Constructive Cooperative Coevolution for Optimising Interacting Production Stations

ARUN RAMANATHAN BALACHANDRAMURTHI
Fatigue, Creep and Notch-sensitivity of Alloy 718 manufactured by Electron Beam Melting process.

ASHISH GANVIR
Lic 2016
Microstructure and Thermal Conductivity of Liquid Feedstock Plasma Sprayed Thermal Barrier Coatings

CHAMARA KUMARA
Electron beam melting of Inconel 718: Modelling of relationships between microstructure and mechanical properties

ESMAEIL SADEGHIMERESHT
Lic 2016
Corrosion performance of HVAF thermal spray coatings

JOSEFINE SVENUNGSSON
Modelling and simulation of laser welding

MORGAN NILSEN
Sensor-based control of laser welding in difficult to access areas

NAGESWARAN TAMIL ALAGAN
Investigation of Heat Dissipation in Boundary Layer Interaction of Tool-Fluid in HRSA Machining with Forced Coolant Application

SNEHA GOEL
Post treatment of Alloy 718 component built by Electron Beam Melting

TAHIRA RAZA
Influence of process parameters on the laser powder bed fusion additive manufacturing technology of super-alloys

ACADEMIC THESES

Licentiate theses:

Devotta, A. M. (2015)
Characterization & modeling of chip flow angle & morphology in 2D & 3D turning process. (Licentiate dissertation). Trollhättan: University West.

Ganvir, A. (2016)
Microstructure and Thermal Conductivity of Liquid Feedstock Plasma Sprayed Thermal Barrier Coatings. (Licentiate dissertation). Trollhättan: University West.

Hosseini, V. (2016)
Influence of multiple welding cycles on microstructure and corrosion resistance of a super duplex stainless steel. (Licentiate dissertation). Trollhättan: University West.

Magalhães, A. (2016)
Thermo-electric temperature measurements in friction stir welding: Towards feedback control of temperature. (Licentiate dissertation). Trollhättan: University West.

Mahade, S. (2016)
Functional Performance of Gadolinium Zirconate/Yttria Stabilized Zirconia Multi-Layered Thermal Barrier Coatings. (Licentiate dissertation). Trollhättan: University West.

Sadeghimeresht, E. (2016).
Corrosion Behavior of HVAF-Sprayed Bi-Layer Coatings. (Licentiate dissertation). Trollhättan: University West.

Svenman, E. (2016).
Inductive measurement of narrow gaps for high precision welding of square butt joints. (Licentiate dissertation). Trollhättan: University West.

PhD theses:

Charles Murgau, C. (2016).
Microstructure model for Ti-6Al-4V used in simulation of additive manufacturing. (Doctoral dissertation). Luleå: Luleå tekniska universitet.

Javidi Shirvan, A. (2016).
Modelling of cathode-plasma interaction in short high-intensity electric arc: Application to Gas Tungsten Arc Welding. (Doctoral dissertation). Göteborg: Chalmers University of Technology.

Åstrand, E. (2016).
A Framework for optimised welding of fatigue loaded structures: Applied to gas metal arc welding of fillet welds. (Doctoral dissertation). Trollhättan: University West.

SiCoMaP – INDUSTRIAL RESEARCH SCHOOL

The SiCoMaP research school has been up and running since 2012. It is funded by the KK Foundation and is run in close cooperation with a number of manufacturing industries. The name of the research school is "Simulation and Control of Material affecting Processes" or in short SiCoMaP. The driving forces are reduced manufacturing cost in parallel with increased quality and reduced environmental footprint.

The school emphasizes simulation and control of material affecting processes. This multidisciplinary approach will increase mutual understanding of underlying physics and what is feasible to control. Two major research areas are addressed: production processes and production systems. In both areas simulation technology includes modelling and implementation in realistic situations. Frontline tools for simulation and control are used to enhance product design and increase flexibility in production.

Participating companies: GKN Aerospace, Innovatum, SWEREA IVF, SWEREA Kimab, Sandvik Coromant, Scania, Seco Tools, Uddeholm and Volvo CE

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ADNAN AGIC
SECO TOOLS
Dynamic analysis and optimization of machining

AMIR PARSIAN
SANDVIK, Lic 2016
Dynamics of torsional and axial vibrations in indexable drills

ANA BONILLA
GKN
Advanced Technology Data and Part Programming

ANDERS JOHANSSON
SCANIA
Development of innovative process for machining system acquisition

ARBAB REHAN
UDDEHOLM
Optimised cold work tool steel for cutting AHSS

ASWIN DEVOTTA
SANDVIK, Lic 2016
Influence of cutting insert macro geometry on chip formation

EDVARD SVENMAN
GKN, Lic 2016
Improved and novel online measurement techniques for more robust laser welding and detection of flaws

ERIK ÅSTRAND
VOLVO CE
Robust weld procedures for fatigue optimized structures

HENRIK JÄGER
SWEREA KIMAB
Material aspects of high performance stainless steels and Ni-based aerospace alloys and their link to tool wear and surface integrity in component machining

JOACHIM STEFFENBURG-NORDENSTRÖM, GKN
Virtual simulation for robust manufacturing of fabricated aero engine components

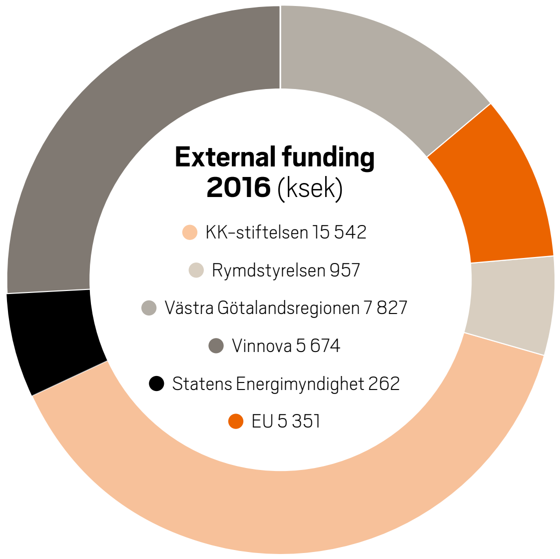
JONAS HOLMBERG
SWEREA IVF
Surface integrity of machined advanced alloys

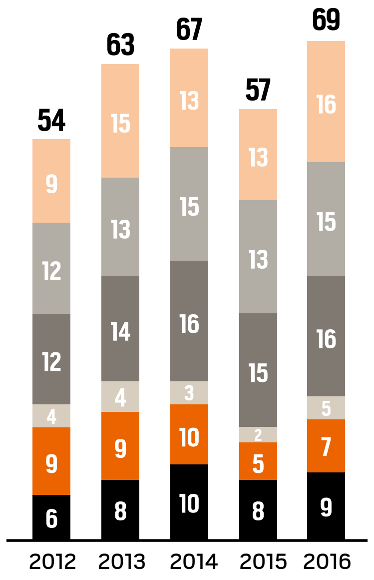
KARL FAHLSTRÖM
SWEREA KIMAB, Lic 2016
Material & Process Solutions for Future Vehicles

MARIA TERESA COLL FERRARI
UDDEHOLM, Lic 2016
Understanding industrially Relevant Heat Treatments and Resulting Microstructures for Large Die Casting Tools

SATYAPAL MAHADE
INNOVATUM, Lic 2016
Multi Layered Thermal Barrier Coatings for High Temperature Applications

VAHID HOSSEINI
INNOVATUM, Lic 2016
Influence of complex thermal cycles on microstructure and properties of welds in highly alloyed stainless steels

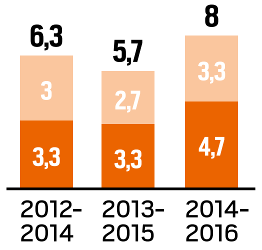




Total number of research personnel at PTW

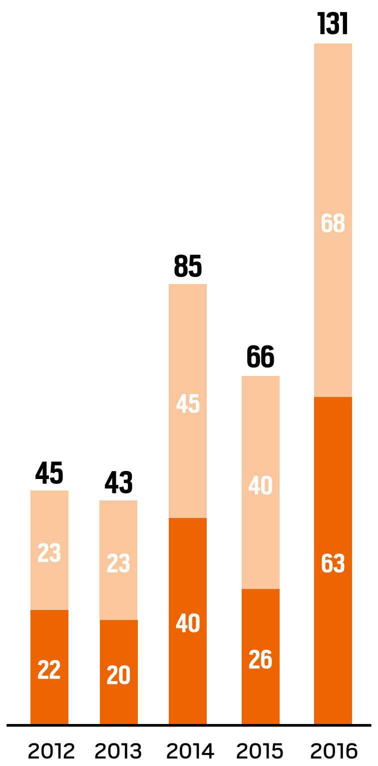
- Engineers
- PhD students
- Lecturer
- Assoc professors
- Guest professors
- Professors

FACTS AND FIGURES



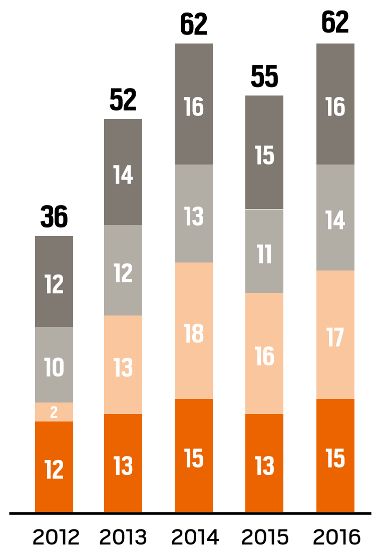
Examina in average over 3 year period

- PHD examina
- Licentiate examina



Publications PTW

- Journals
- Conferences



PhD-students and Supervisors PTW

- Other supervisors
- Main supervisors
- Industrial PhD-students
- PhD students

JOURNAL PUBLICATIONS

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Javidi Shirvan, A., Choquet, I., Nilsson, H. & Jasak, H. (2016). Coupling boundary condition for high-intensity electricarc attached on a non-homogeneous refractory cathode. .

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Hosseini, V. A., Wessman, S., Hurtig, K. & Karlsson, L. (2016). Nitrogen loss and effects on microstructure in multipass TIG welding of a super duplex stainless steel. Materials & design, 98(May), 88-97.

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Kumar, S., Vidyasagar, V., Jyothirmayi, A. & Joshi, S. (2016). Effect of Heat Treatment on Mechanical Properties and Corrosion Performance of Cold-Sprayed Tantalum Coatings. Journal of thermal spray technology (Print), 25(4), 745-756.

Valleti, K., Krishna, D. M., Reddy, P. M. & Joshi, S. (2016). High temperature stable solar selective coatings by cathodic arc PVD for heat collecting elements. Solar Energy Materials and Solar Cells, 145(3), 447-453.

Gupta, M. K., Weber, A., Markocsan, N. & Helden, N. (2016). Development of plasma sprayed Ni/YSZ anodes formetal supported solidoxide fuel cells. Surface & Coatings Technology.

Kumar, R., Govinadarajan, S., Janardhana, R. K., Rao, T. N., Joshi, S. & Anandan, S. (2016). Facile One-Step Route for the Development of in Situ Cocatalyst-Modified Ti3+ Self-Doped TiO2 for Improved Visible-Light Photocatalytic Activity. ACS Applied Materials and Interfaces, 8(41), 27642-27653.

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Sundararajan, G., Joshi, S. & Rama Krishna, L. (2016). Engineered surfaces for automotive engine and power train components. Current Opinion in Chemical Engineering, 11, 1-6.

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