KME

CONSORTIUM MATERIALS TECHNOLOGY for demonstration and development of thermal energy processes

KME – Consortium Materials technology for demonstration and development of thermal energy processes

Final report from phase V – programme period 2010–2013

Bertil Wahlund

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Preface

The report is summarising the work that has been performed within the framework of the fifth stage of the material technology research programme KME.

KME, Consortium Materials technology for demonstration and development of thermal Energy processes, was established 1997 on the initiative of energy industries and the Swedish Energy Agency. In the consortium, the Swedish Energy Agency, seven industrial companies and 18 energy companies participate. The programme stage has been financed with 60.2 % by participating industrial companies and with 39.8 % by Swedish Energy Agency. The consortium is managed by Elforsk.

The programme shall contribute to increasing knowledge to forward the development of thermal energy processes for various energy applications through improved expertise, refined methods and new tools. The programme shall through material technology and process technology developments contribute to making electricity production using thermal processes with renewable fuel more effective. This is achieved by

- Forward the industrial development of thermal processes through strengthening collaboration between industry, academy and institutes.
- Build new knowledge and strengthen existing knowledge base at academy and institutes
- Coordinate ongoing activities within academy, institutes and industry

KME's activities are characterised by long term industry relevant research and constitutes an important part of the effort to promote the development of new energy technology with the aim to create an economic, environmentally friendly and sustainable energy system.

Sammanfattning

Konsortiet Materialteknik för demonstration och utveckling av termiska energiprocesser, KME, bildades 1997 på initiativ av energiindustrin och Energimyndigheten. Programmets femte etapp, perioden 2010-2010, är nu avslutad och redovisas översiktligt i föreliggande slutrapport. Alla under programperioden genomförda projekt redovisas dessutom i separata slutrapporter som kan nedladdas från KME:s webbplats www.kme-elforsk.se.

Intressenter och kunder (finansiering 60,2 %) till den femte programetappen är följande industriföretag:

- GKN Aerospace Sweden AB (Volvo Aero)
- Outokumpu Stainless AB
- Sandvik Heating Technology AB
- Sandvik Materials Technology AB
- Siemens Industrial Turbomachinery AB
- Valmet Power AB (Metso Power)
- Energiföretagen via Elforsk AB:
    - AB Fortum Värme samägt med Stockholm stad
    - DONG Energy AS
    - E.ON Climate and Renewables
    - E.ON Värme Sverige AB
    - Ena Energi
    - Eskilstuna Energi & Miljö AB
    - Falu Energi
    - Göteborg Energi AB
    - Kraftringen
    - Mälarenergi AB
    - Skellefteå Kraft AB
    - Svensk Fjärrväme
    - Söderenergi
    - Tekniska Verken i Linköping AB
    - Umeå Energi AB
    - Vattenfall AB
    - Växjö Energi
    - Öresundskraft AB

Energimyndigheten svarar för statlig medfinansiering till programmet med 39,8 %. Samtliga industriföretag har varit representerade i programmets styrelse och styrgrupper tillsammans med representanter för Energimyndigheten, högskolor och forskningsinstitut.

Elforsk har svarat för programhanteringen och varit formell stödmottagare för statliga forskningsanslag från Energimyndigheten.

Forskningen inom KME inriktas på projektorienterade materialprov och materialutveckling i laboratorier och anläggningar med avseende på

hållfasthet, korrosion, tillverkning och fogning, samt att genom nyttiggöra programmets forskningsresultat och kunskaper, demonstrera högre elverkningsgrader i energiprocesser baserade på förnybara bränslen. Resultaten ska vara tillämpbara efter cirka 5 år. Inriktningen för KME-programmet femte programetapp, 2010-2013:

- Utveckling av modellanläggningskoncept som underlag för demonstration av 3-4 procentenheter högre elverkningsgrad i kraftvärmeanläggningar med avancerad ångdata.
- Utveckling och ökad kunskap kring nya överhettarmaterial och konstruktionslösningar vid användning av förnybara bränslen
- Utveckling och ökad kunskap kring avancerade material för gasturbiner, pannor och ångturbiner i högtemperaturapplikationer
- Prestandaförbättrande materialfrågor för gasturbiner.

Projekten har genomförts inom ramen för projektavtal mellan en eller flera industriparter, Elforsk och en högskola eller forskningsinstitut.

Under programetappen har totalt 22 st forskningsprojekt genomförts. Föreliggande slutrapport innehåller sammanfattningar från resultaten i de enskilda projekten. För de som vill fördjupa sig i de enskilda projektresultaten hänvisas till projektslutrapporterna på programmets webbplats enligt ovan. Utöver forskningsprojekten, KME har genomfört en syntes av hela forsknings-programmet KME.

Summary

Consortium Materials technology for demonstration and development of thermal energy processes, KME, was established in 1997 after an initiative from energy industries and the Swedish Energy Agency. The fifth programme phase 2010-2013 is presented in summary in this final report. In addition the results from the different projects are also available in project reports and can be down loaded from the programme webpage www.kme-elforsk.se.

The following companies have been stakeholders (finance 60.2 %) during the fourth programme period:

- GKN Aerospace Sweden AB (Volvo Aero)
- Outokumpu Stainless AB
- Sandvik Heating Technology AB
- Sandvik Materials Technology AB
- Siemens Industrial Turbomachinery AB
- Valmet Power AB (Metso Power)
- Energy companies via Elforsk AB:
  - AB Fortum Värme samägt med Stockholm stad
  - DONG Energy AS
  - E.ON Climate and Renewables
  - E.ON Värme Sverige AB
  - Ena Energi
  - Eskilstuna Energi & Miljö AB
  - Falu Energi
  - Göteborg Energi AB
  - Kraftringen
  - Mälarenergi AB
  - Skellefteå Kraft AB
  - Swedish district heating association
  - Söderenergi
  - Tekniska Verken i Linköping AB
  - Umeå Energi AB
  - Vattenfall AB
  - Växjö Energi
  - Öresundskraft AB

The contribution to the programme financing from the Swedish Energy Agency has been 39.8 %. Representatives from the stakeholders, universities, research institutes as well as from the Swedish Energy Agency have been members of the programme board, and steering committees.

Elforsk has been responsible for the administration of the programme and also receiver and administrator of the government research grant.

The research within KME is focused on project oriented material tests and material development and research in laboratories and power plants,

concerning strength, corrosion, manufacturing and welding, as well as through using research results from programme and knowledge, demonstrate enhanced electrical efficiencies in energy processes based on renewable fuels. The results shall be ready for implementation after approximately five years. The work within the fifth programme phase, 2010-2013, has been concentrated on:

- Development of model plant concept as the basis of demonstration of 3-4 percentage units increase in electrical efficiency in CHP plants with advanced steam data
- Development and increased knowledge of new superheater materials and construction solutions with the use of renewable fuels.
- Development and increased knowledge of advanced materials for gas turbines, boilers and steam turbines in high temperature applications
- Material issues to improve performance of gas turbines

The projects have been performed based on project agreements between one or several industrial partners, Elforsk and universities or research institutes.

During the programme period, in total 22 projects have been accomplished. To enter more deeply into project results, please see the project reports available on the programme website as mentioned above. In addition to the research projects, KME has conducted a synthesis of the entire KME research programme.

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Appendix

1 Introduction

1.1 Background

KME was established in 1997 after an initiative from energy industries and the Swedish Energy Agency, with ten industry stakeholders as participants. The programme research content and budged was extended in 1998, when two new stakeholders joined. A further extension of programme was made at the initiation of the fifth programme phase 2010-2013, when the programme was complemented with a new programme area "More effective electricity production from renewable fuels", with the focus on demonstration and development of thermal energy processes. The programme has been conducted in the following programme stages:

- Programme stage I, 1997-2000
- Programme stage II, 2001-2004
- Programme stage III,2005 (one year)
- Programme stage IV, 2006-2009
- Programme stage V, 2010-2013, presented in the report
- Programme stage VI, 2014-2017, currently starting up

General information regarding programme can be found on web site www.kme-elforsk.se. Publications from previous stages and publication list can also be found at the web site.

The activities within KME's research programme have been marked by continuity between the different programme stages, i.e. it has usually been the case that begun projects have been completed and advanced or deepened in successive stages of the programme. The stakeholder group have also been stable with some minor changes throughout the years. The KME programmes have contributed to joint projects and information transfere between material suppliers, system manufactors and end users.

A significant partial result of the KME programme is that since it started in 1997 it has led to many PhD and licentiate degrees being awarded at the universities. This work is in many cases financed jointly by KME and HTC. A follow-up of the students awarded PhD degrees in June 2009 shows that they are employed by companies in the sector doing important and relevant work within material technology at, for example, Siemens, Sandvik Heating Technology, Sandvik Materials Technology, Volvo Aero/GKN, Vattenfall as well as KIMAB. Some have remained at universities as post docs, which naturally contributes to increasing knowledge in the field.

The KME programme has contributed to significant knowledge and technological advancement within the field of material technology where, for example, initial tests with superheaters in loop seal for CFB boilers were started at KME. Important work has also been conducted to contribute to knowledge regarding super heater corrosion with renewable fuels and development of new steel alloys (9-12% Cr-steel) that is now designed into steam turbines.

2 Stakeholders and partners

The fifth programme stage of KME 2010-2013 was financed by industries (60.2 %) and by the Swedish Energy Agency (39.8 %. The industry stakeholders in the fifth programme stage, were the following industry companies:

- GKN Aerospace Sweden AB (Volvo Aero)
- Outokumpu Stainless AB
- Sandvik Heating Technology AB
- Sandvik Materials Technology AB
- Siemens Industrial Turbomachinery AB
- Valmet Power AB (Metso Power)
- Energy companies via Elforsk AB:
    - AB Fortum Värme samägt med Stockholm stad
    - DONG Energy AS
    - E.ON Climate and Renewables
    - E.ON Värme Sverige AB
    - Ena Energi
    - Eskilstuna Energi & Miljö AB
    - Falu Energi
    - Göteborg Energi AB
    - Kraftringen
    - Mälarenergi AB
    - Skellefteå Kraft AB
    - Swedish district heating association
    - Söderenergi
    - Tekniska Verken i Linköping AB
    - Umeå Energi AB
    - Vattenfall AB
    - Växjö Energi
    - Öresundskraft AB

The industry stakeholders were represented in the programme board together with representatives from Swedish Energy Agency, academia and research institutes. The programme board is formally approved by the Swedish Energy Agency, and consisted of the following members:

Erik Skog (chairperson)	Chalmers
Bengt Gudmundsson	Siemens Industrial Turbomachinery AB
Magareta Lundberg	Valmet (Metso Power)
Per Kallner	Vattenfall
Bengt-Åke Andersson	E.ON Värme Sverige AB
John Hald	Dong Energy

Eva-Katrin Lindman	AB Fortum Värme samägt med Stockholms stad
Bo Jönsson	Sandvik Heating Technology AB
Oliver Lindqvist	Chalmers
Mikko Hupa	Åbo Akademi

Adjunct members:

Sofia Andersson	Energimyndigheten
Camilla Axelsson	Energimyndigheten
Helena Oskarsson	Siemens Industrial Turbomachinery AB
Mats Åbjörnsson	E.ON Värme Sverige AB
Lars Hammar	Kraftringen/Lunds Energi AB
Lars Wrangensten	Elforsk AB (programme manager KME) to 2012
Bertil Wahlund	Elforsk AB (programme manager KME) from 2012

Table 1. Financing of 2010-2013 programme.

Company	**Total, kSEK per 4 years**	**Base programme, kSEK per 4 years**	**EPP programme, kSEK per 4 years**	**Included cash, kSEK per 4 years**
Siemens IT*	17 660	10 860	6 800	160
GKN (Volvo Aero)	5 850	5 850	0	160
Sandvik Heating Technology AB*	5 262	5 062	200	160
Sandvik Materials Technology	4 720	4 720	0	840
Outokumpu	2 760	2 160	600	160
Valmet (Metso) Power *	1 992	0	1 992	160
Energy companies via Elforsk				
Vattenfall*	9 827	4 823	5 004	1 412
E.ON Värme Sverige AB*	3 000	2 000	1 000	160
E.ON Climate and renewables (UK)	2 000		2 000	
Dong Energy*	2 000	160	1 840	160
Fortum värme*	1 937	537	1 400	760
Swedish district heating association	920	0	920	920
Göteborg Energi	800	160	640	800
Mälarenergi	704	160	544	704
Skellefteå Kraft	560	160	400	560
Växjö Energi	400	0	400	400
Öresunds Kraft	400	0	400	400
Kraftringen Produktion AB (Lunds Energi)*	400		400	400
Söderenergi	352	80	272	352
Ena Energi	260	0	260	260
Eskilstuna Energi & Miljö	160	80	80	160
Umeå Energi	160	0	160	160
Falu Energi & Vatten	80	0	80	80
Tekniska Verken i Linköping	44	44	0	44
Total sum from industry, kSEK	**62 248**	**36 856**	**25 392**	**9 372**
Swedsh Energy Agency (40%), kSEK	**41 227**	**24 299**	**16 928**	
Sum, total kSEK	**103 475**	**61 155**	**42 320**	

*Board member

3 Programme management

Elforsk, the electric utilities R&D company, has been responsible for all programme management, follow up and results dissemination. Elforsk has participated as adjunct member of board and steering committees, and executed all board decision such as purchase order, project agreement, approval of reports and arrangement of annual programme conferences.

4 Programme focus, vision and goals

4.1 General programme focus and organisation

The research within the KME programme have been directed towards project related material test and materials development in labs and plants, as well as process related development, regarding material strength, corrosion, manufacturing and welding, which are needed for enable verifying of new solutions. The results shall be applicable after approximately five years.

The activities within the KME programme are divided into two sub programmes; the base programme on material technology (MATBAS) and the programme area More Effective Power Production (EPP). Each sub programme had a steering committee but the KME programme board was responsible for all activities within the programme.

The programme area More effective electricity production included, on the part of KME, partly new activities within process and plant technology, with the goal of successively being able to demonstrate more effective and profitable thermal processes for electricity production. The base programme was a direct continuation of KME's activities in previous programmes and was oriented towards the principal areas development of materials technology solutions for boilers and performance improvement material questions for gas turbines and steam turbines.

4.2 Vision

The long term vision of the programme was, on the basis of materials technology development, to enhance electrical efficiency and total efficiency using renewable fuels in thermal energy conversion processes.

The long term goal of the programme included, within the time perspective 2017-2018, to facilitate a demonstration a new full-scale combined heat and power plant based on renewable fuels and waste fuels primarily made up of renewable fractions with between 3-4 percentage units increased electrical efficiency.

4.3 Objective

The objective was to make possible the effective production of electricity and heat with high fuel flexibility, minimal environmental impact, good partial load properties with a limited heat load.

4.4 Goals

The overarching goal is that the programme shall contribute to a conversion to sustainable power production systems through the development of more effective thermal processes.

For the programme period, KME had the following goals:

- Presentation of technical solution for a commercial feasible reference power plant as a basis for the demonstration plant
- Deeper understanding and knowledge of material process solutions to prevent super heater and furnace corrosion with advanced steam data
- Lab tests to appoint mechanisms affecting material life time during new advanced steam data requirements
- Exposure tests with partly new boiler super heater materials and compare them with results from cooled material probe tests
- Exposure tests with new alumina forming FeCrAl-materials and explore the possibilities for future use
- Development of improved analysis methods to determine weldability of Ni–based super alloys
- To show that conventional materials can be joined by welding with high temperature materials in order to get more cost effective solutions
- Integration between a new KME-project and the international welding project Weldmat for increased knowledge base
- Validation of materials and surface coatings for coming industrial gas turbine plants optimised for requirements concerning efficiency and robust design (availability and long technical life time)
- Continue building networks between universities and industry

5 Project accomplishment

The projects within KME are conducted within the framework of a specific project agreement agreed and signed by one or more industrial stakeholders, Elforsk and a university or research institute. The university or research institute's work is financed by cash funds from Elforsk and the project is conduced as a cooperation and support from the industrial stakeholders. The industrial stakeholders participate with own in-kind contributions according to chapter 2 above as working hours, materials, analyses, equipment etc. In addition to the research projects, KME has conducted a synthesis of the entire KME research programme.

The following research projects have been conducted within the current program period.

Table 2 KME Projects in the Materials Technology Base Programme 2010–2013

Project	Project Name	Performed by	Industry Partners	Project Manager
KME 501	Long term high temperature behaviour of advanced heat resistant materials	Linköping University	AB Sandvik Materials Technology	Sten Johansson
KME 502	Fatigue in nickel-based superalloys under LCF and TMF conditions	Linköping University	Siemens	Johan Moverare
KME 503 KME 520 (extension)	New Durable MCrAlX Coatings for High Temperature and Corrosive Environment Applications in Advanced Engines	Linköping University	Siemens	Ru Peng
KME 504	Correlation between deposit chemistry and initial corrosion of super heaters	Swerea KIMAB and SP	Vattenfall	Rikard Norling
KME 505	Properties of alloyed MoSi2 matrix composite for hot corrosion and elevated temperature components of gas turbine	Chalmers	Siemens and Sandvik Heating Technology	Yiming Yao
KME 506 KME 518 (extension)	Weldability Limits for Superalloys in High Temperature Applications for Gas Turbines	Chalmers	GKN Aerospace	Lars Nyborg
KME 507	FeCrAl alloys for components in biomass and refuse fuelled boilers – prestudy	HTC	Sandvik Heating Technology, E.ON Värme, Vattenfall and Valmet Power	Kristina Hellström
KME 508 KME 515 (extension)	Furnace wall corrosion in biomass and waste-fired boilers at higher steam pressures	KIMAB, SP and KTH	Sandvik Heating Technology, Sandvik Materials Technology, Outokumpu, E.ON Värme, Vattenfall, E.ON Climate and Renewables and Valmet Power	Pamela Henderson
KME 509	Concentrated approach on super heater corrosion in boilers fuelled with biomass and refuse	HTC	E.ON Värme and Valmet Power	Jesper Liske
KME 510	Design of a new generation of 12% chromium steels	Chalmers	Siemens and Dong Energy	Hans-Olof Andrén
KME 511	Critical corrosion phenomena in power generation from biomass – Identification of chlorine resistant high temperature coatings/materials	HTC	Dong Energy	Torbjörn Jonsson
KME 512	Fuel additives to reduce corrosion at elevated steam data in biomass boilers	Vattenfall Research and Development, SP, Åbo Akademi	E.ON Värme Sverige, E.ON Climate and Renewables, Valmet, Outokumpu, Sandvik Heating Technology	Maria Jonsson Annika Stålenheim
KME 514	Increased electrical efficiency and service life assessment of super heaters from combustion of difficult fuels	HTC	Fortum	Jesper Liske
KME 519	FeCrAl alloys as components in biomass- and waste fired boilers with sulphur additives	HTC	Sandvik Heating Technology	Kristina Hellström
KME 521	Thermomechanical fatigue in virgin and aged stainless steels	Linköping University	Sandvik Heating Technology	Johan Moverare

Table 3 KME Projects in the Programme Area More Effective Power Production 2010–2013

Project	Project Name	Performed by	Industry Partners	Project Manager
KME 601	More Effective Power Production from Renewable Fuels – Reference Power Plant (RPP)	Erik Skog AB Pöyry Swedpower (former Vattenfall Power Consultant)	Siemens, Valmet Power, Vattenfall, E.ON Värme, Fortum Värme, Kraftringen Produktion, Svensk Fjärrvärme, Göteborg Energi, Mälarenergi, Skellefteå Kraft, Växjö Energi, Öresundskraft, Söderenergi	Erik Skog
KME 607	Improved steam turbine design for optimum efficiency and reduced cost of ownership	Lund University	Siemens Industry Turbine	Magnus Genrup
KME 608	Study of corrosion memory in boiler heat surfaces by field tests with biomass fuel mixes including sulphur and refuse fractions	Pöyry Swedpower (former Vattenfall Power Consultant)/HTC	E.ON Värme, E.ON Climate and Renewables, Sandvik MT	Lars Wrangensten Tom Sandberg
KME 609	Technical and economical risks for plant concepts with advanced steam data for biomass-fired CHP demonstration plant	Vattenfall R&D, Pöyry	Vattenfall, E.ON, Siemens, Valmet	Raziyeh Khodayari

6 Scientific and technical results

All projects have been reported in a final report approved by the KME board. The projects are presented briefly below and summaries from the projects are presented in annex 1. In addition to the research project reports, KME has summaries the programme results in a separate report *Synthesis of the KME Research Programme*.

6.1 Sub programmes

The programme activities were divided into two sub programmes with the following research areas:

Programme area More effective electricity production from renewable fuels

- Applied process and plant technology development for more profitable thermal processes for electricity production

Materials technology base programme

- Development of materials technology solutions for boilers
- Performance improvement material questions for gas turbines and steam turbines

6.2 Projects within More effective electricity production from renewable fuels

Project KME-601 More Effective Power Production from Renewable Fuels – Reference Power Plant (RPP)

Project leader: Erik Skog, Erik Skog AB

The goal for the project is to create and evaluate high efficient, and competitive, model concepts - Reference Power Plant(s) “RPP”. The project object is also to identify and evaluate supporting R&D projects in line with KME programme and required for a future demonstration.

The project goal to increase the electrical efficiency of 3-4% units can be achieved with renewable fuels. Profitability is possible with pure forest fuels for plants of the 100 MW_e size. The efficiency increase is somewhat lower for Swedish conditions. For renewable fuels with 75% recycled wood it's profitable for the plant size from 25 MW_e and above. For installations with condensing operating profitability is very good. A list of nine supporting R&D activities has been identified.

Project KME 607 Improved steam turbine design for optimum efficiency and reduced cost of ownership

Project leader: Magnus Genrup, LU

The cost of ownership of a power plant is partly governed by the efficiency of the turbine island. The efficiency of an industrial size steam turbine can be increased by an improved steam-path design. Most industrial size units have fairly simple prismatic blades in a significant part of the turbine. Development in manufacturing technology has levelled the cost for more advanced geometries and offers higher performing turbines.

The project aim is to introduce improved blade profiles and advanced stacking technologies in industrial steam turbines used in the larger utility type of turbines, and by that increase the turbine efficiency. The work has been carried out in state-of-the-art turbine design tools and comprises: one-dimensional tool, two-dimensional throughflow analysis and full three-dimensional high-fidelity CFD.

The work shows that the stage performance can be increased. To be further studied in continued work.

Project KME-608 Study of corrosion memory in boiler heat surfaces by field tests with biomass fuel mixes including sulphur and refuse fractions

Project leader: Lars Wrangensten and Tom Sandberg, Pöyry

An increased knowledge of the relationship between dynamic corrosion mechanisms, fuel specification and possible steam operation temperatures can form a platform for how to implement gliding steam temperature control. A key phenomenon can be referred to as the corrosion attack during operation due to historic boiler operation (corrosion memory). By studying both the kinetics of artificial deposits in real boiler as well as actual corrosion probe test in two commercial boilers new knowledge about the corrosion memory effect have been obtained. The tree main important questions to be answered in project:

1. Can the corrosion rate be maintained low after a change to a more corrosive fuel if the steam temperature is lowered at the same time?
2. Is there a memory effect (resulting in increased corrosion rate) after the return to high steam temperature and less corrosive fuel?
3. Is there an “incubation time” (before the corrosion rate increases) for materials exposed at high steam temperature and less corrosive

The corrosion tests indicate a positive “memory effect” both from artificial and actual deposits. An incubation time has also been identified in one exposure time.

Project KME-609 Technical and economical risks for plant concepts with advanced steam data for biomass-fired CHP demonstration plan

Project leader: Raziyeh Khodayari, Vattenfall

This project has studied technical, economic and other project risks that can be present during a demonstration phase of a biomass-fired plant with advanced steam data. The purpose has been to support finding a site and host for the demonstration plant. Fall-back options have been defined with the prerequisites to identify a fail-safe mode with the highest economic feasibility. From KME-601, the following two plant concepts were selected:

1. Virgin biomass fuels, 100 MWe, with advanced steam data 175 bar/600°C
2. Wide fuel mix, 50MWe, with advanced steam data 160 bar/563°C

For the virgin fuel case, the main technical risks are creep and fatigue in superheater, turbine availability and steam side oxidation. For the wide fuel case, the most important risks are corrosion and increased metal loss in furnace wall and heat exchanger surfaces as evaporator and superheater.

6.3 Projects within Materials technology base programme

6.3.1 Development of materials technology solutions for boilers

Project KME-501 Long term high temperature behaviour of advanced heat resistant materials

Project leader: Sten Johansson, LiU

The presented research within this work deals with high-temperature behaviour of austenitic alloys, five austenitic stainless steels and two nickel base alloys, with focus on deformation, damage and fracture behaviour during slow strain rate deformation and the influence of long term ageing.

Increased knowledge about the mechanical performance of austenite materials for future application in the area of power generation has been achieved. The results show that the structural development during testing is affecting properties differently depending on alloy composition and applied strain rate. It was found that the main deformation mechanisms in the austenitic alloys are planar dislocation deformation, such as planar slip, slip bands in single and multi-direction.

Project KME-504 Correlation between deposit chemistry and initial corrosion of superheaters

Project leader: Rikard Norling

The goal with the project was to increase the detailed knowledge and understanding regarding the effect of increased steam temperatures and the controlled use of additives, e.g. sulphur-containing, on deposit formation and initial corrosion of superheater tubes. The main focus in the project has been to analyse deposits and materials from pilot-scale tests, using controlled dosage of S and P, through pilot scale exposures. Tests have also been performed and compared with samples from full scale testing.

It was found that ammonium sulphate is more effective compared to mono ammonium phosphate in reducing the chloride content in deposits. When adding ammonium sulphate it is concluded that the oxygen level in the boiler is more important than the dosage of additive in order to decrease the chloride content efficiently. This information is highly valuable since the excess air ratio is typically decided from other criteria than corrosion, such as economic.

Project KMME-507 FeCrAl alloys as components in biomass- and waste- fired boilers

Project leader: Kristina Hellström

The aim of this project was to identify and understand the usability and the limitations of alumina forming materials as components in biomass- and waste fired combustion plants. The work was focused on identifying mechanisms behind the corrosion and to find ways to alleviate the high temperature corrosion problems, and included an initial lab study in and field exposures in a waste fired boiler.

The results show that the corrosion resistance of certain components of the waste-fired boilers can be improved significantly if the existing material is replaced with FeCrAl material, such as thermo shield tubes and superheaters (as coatings due to the pressure load). The surprising result that the pre-oxidation is not favourable when the material is used at temperatures below 700°C means that production of major boiler components in FeCrAl material would be greatly facilitated.

Project KME-508 Furnace wall corrosion in biomass-fired boilers at higher steam temperatures and pressures

Project leader: Pamela Henderson

The project overriding goal is to give recommendations about how to avoid water wall corrosion at increased boiler electrical efficiency/increased steam data when burning biomass and waste wood mixes.

In this project, ways of reducing furnace wall corrosion have been investigated. The wall deposit chemistry and furnace flue gases have been characterised to get a better understanding of the environment, and long-term corrosion tests of standard wall material and different candidate coating materials have been performed.

It was found that furnace wall corrosion in recycled wood fired boilers can be reduced by coating the walls with the Ni-base alloy IN 625. Stainless steel coatings also worked well and an FeCrAl alloy showed potential. Overlay weld coatings had better adherence than thermally sprayed coatings. The use of treated sewage sludge changed the composition of the deposits and reduced corrosion during short-term testing.

Project KME-509 Improved determination of service life of superheaters in boilers burning biomass and waste

Project leader: Jesper Liske

The main aim of this project has been to improve the plant economy by generating fundamental knowledge about how probe exposures can be used in order to estimate the lifetime of the superheater. The corrosion rate obtained from the probe exposures usually exaggerates the actual corrosion rate of the superheaters. This aim has also been addressed by KME-514. The project focuses on understanding the discrepancy between corrosion rate measurements using cooled probes and the corrosion rate of the real superheater, by comparing time resolved cooled probe corrosion rate measurements with exposures of sample materials installed in the superheater tube loop.

The project has demonstrated how corrosion rates change over time, the importance of having the probe exposures mimicking the thermal and environmental history of the superheaters, compared the corrosion rate at the existing temperature and at an elevated temperature, 80°C higher than the existing one. The conclusion is that probe exposures can be used for estimating the potential corrosion rate of superheaters.

Project KME-510 New Martensitic Steels for Steam Power Plants with Higher Efficiency

Project leader: Hans-Olof Andrén/Fang Liu, Chalmers

All attempts so far to exceed 600-620°C with 11-12% chromium steels have failed due to precipitation of a complex nitride, Z-phase, leading to a dramatic fall in creep strength, after a few years of service. This project aims at contribute to the development of a new generation of martensitic chromium steels that use Z-phase as a strengthening rather than weakening phase. The new steels have the potential to be used as piping or superheater tubing in future biomass power plants.

The new concept to use finely distributed Z-phase to strengthen 12% chromium steels, to achieve good corrosion resistance and creep strength for high temperature applications, is feasible. Compared to Nb, Ta is a better candidate to form fine Z-phase precipitates. Cu addition can modify the distribution of Laves phase, and yield desirable impact toughness.

Project KME-511 Critical corrosion phenomena in power generation from biomass – Identification of chlorine resistant high temperature coatings/materials

Project leader: Torbjörn Jonsson, Chalmers

Combustion of biomass results in a much more corrosive fireside environment compared to the combustion of fossil fuels such as coal. The corrosive properties of the fuel have mainly been attributed the high alkali chlorine content. The overall goal of the project was to identify a possible material for superheater tubes, which allows an outlet steam temperature of at least 580°C on biomass converted fossil-fired units. In the present project superheater samples from a biomass fired boiler have been investigated, thermodynamic calculations and screening experiments have been performed in order to identify a possible corrosion resistant coating.

By studying field exposed samples and performing thermodynamic calculations the Ni-Al material system was identified as a possible alkali chloride resistant coating/material. The Ni-Al system was in addition tested through laboratory exposures where the Ni_2Al_3 coating formed a protective aluminium rich scale in the presence of KCl.

Project KME-512 Fuel additives to reduce corrosion at elevated steam data in biomass boiler

Project leader: Annika Stålenheim/Maria Jonsson, Vattenfall

Wide fuel mixes are of interest for many energy companies. However, wide fuel mixes contain components causing corrosion in the furnace and convective superheaters, especially wall corrosion. The project goal was to identify and then evaluate and give recommendations for the use of additives and fuel blends to reduce furnace wall, and possibly also superheater, corrosion for wide biomass fuel mixes including waste wood.

Five additives were selected and tested in a fluidised bed combustion test rig. As a result of these tests, two additives, digested sewage sludge and kaolin, were found to have a positive effect on waterwall corrosion as well as on superheater corrosion when burning waste wood.

Project KME-514 Increased electrical efficiency and service life assessment of super heaters from combustion of difficult fuels

Project leader: Jesper Liske, Chalmers

The main aim of this project has been to improve the plant economy by generating fundamental knowledge about how probe exposures can be used in order to estimate the lifetime of the superheater. The corrosion rate obtained from the probe exposures usually exaggerates the actual corrosion rate of the superheaters. This aim has also been addressed by KME-509. The project does also aim for increasing the understanding of deposit build-up and fouling and the aim to increase the steam temperature by at least 50°C from 450 to 500°C for waste fractions, by increased material temperatures of a selection of the samples exposed by probes. The project focuses on understanding the discrepancy between corrosion rate measurements using cooled probes and the corrosion rate of the real superheater. This is done by comparing time resolved cooled probe corrosion rate measurements with exposures of sample materials installed in the superheater bundle.

The project shows how probe exposures and tube exposures correlate and how the corrosion rates change over time. The deposit formation has been coupled to the flue gas chemistry and fuel composition for short term exposures. The conclusion from the project is that probe exposures are a relevant for estimating the life time of superheaters.

Project KME-519 FeCrAl alloys as components in biomass- and waste fired boilers with sulphur additives

Project leader: Kristina Hellström, Chalmers

The aim of this project was to identify and understand the usability and the limitations of alumina forming materials as components in biomass- and waste fired combustion plant. The work was focused on identifying mechanisms behind the corrosion and to find ways to alleviate the high temperature corrosion problems. Exposures were performed in laboratory furnaces with a well-controlled atmosphere.

The results show that the alumina forming FeCrAl material Kanthal APMT is not completely inert to KCl in an oxidizing SO_2 containing atmosphere. However, the corrosion rate is significantly lower than for the chromia forming 304L. Pre-oxidation decreases the corrosion rate even further, making Kanthal APMT a promising candidate material for combustion plant components from a corrosion point of view.

Project KME-521 Thermomechanical fatigue in virgin and aged stainless steels

Project leader: Johan Moverare, LiU

The purpose of this project is to evaluate and rank the susceptibility to thermomechanical fatigue damage of several austenitic materials (well established materials and new potentially better materials) for power plants with biofuel or waste fractions as fuel.

A comparison between Sanicro 25 and AISI 310H shows that the two alloys have essentially the same resistance to thermomechanical fatigue when subjected to mechanical strain ranges lower than 0.6% during IP-TMF with a maximum temperature of 800°C. At higher strain ranges AISI 310 show an advantage due to better ductility. However, Sanicro 25 clearly demonstrates an advantage in strength at both low and high temperatures. Exposure at 800°C promotes the formation of precipitates along grain boundaries in Sanicro 25. These precipitates contribute to the formation of voids and microcracking during tensile straining which leads to a reduction in ductility.

6.3.2 Performance improvement material questions for gas turbines and steam turbines

Project KME-502 Fatigue in nickel-based superalloys under LCF and TMF condition

Project leader: Johan Moverare, LiU

Within the project, mechanical testing and microstructural investigations of deformation and damage have been combined with modelling efforts in order to characterize fatigue in nickel-based superalloys under LCF and TMF conditions. The work demonstrates the importance of anisotropy, tensile/compression asymmetry and localized damage in single crystal superalloys during fatigue. Many of the mechanisms active in single crystals have also been found within the individual grains during deformation of cast polycrystalline materials. A model has been developed within the project that has been proven to capture the most important features seen in the experiments

Project KME-503 New Durable MCrAlX Coatings for High Temperature and Corrosive Environment Applications in Advanced Engines

Project leader: Ru Lin Peng, LiU

The development of coatings providing better oxidation and corrosion protection for hot components in gas turbines for increased availability, operation flexibility and improved efficiency. MCrAlY (M: Ni and/or Co) are widely used as overlays or bondcoats in thermal barrier coating (TBC) systems to protect superalloys operated in the hot sections of gas turbines. The aim of this project is to develop new durable MCrAlX (X: alloying elements of minor addition) optimised for the operation conditions in land based gas turbines of medium size (10-60 MW).

New compositions of MCrAlX coatings exhibiting better oxidation behaviour than reference coatings have been identified and patented. A thermodynamic/kinetic model with potential applications in coating life prediction and alloy design has been established.

Project KME-505 Properties of alloyed MoSi2 matrix composite for hot corrosion and elevated temperature components of gas turbine

Project leader: Yiming Yao

The task of the project is evaluation of mechanical and thermal cycle fatigue properties of the Cr-alloyed composite in comparison with commercial candidate materials (e.g. Si3N4). $MoSi_2$-based composite is one of the candidates due to its higher temperature capability and oxidation resistance superior to superalloys. The goal of the project is to find the application of $MoSi_2$-based materials in the high power-to-heat ratio biomass power generation systems.

The project evidenced that $(Mo_{0.9}Cr_{0.1})Si_2$ +15vol% ZrO_2 composite has high oxidation resistance at 1400°C and remarkable sinterability. A method for ceramic manufacturing, based on mixing/granulation - CIP – pre-sintering – CNC matching – pressure-less sintering (PLS), to produce a prototype of SGT800B turbine heat shield, have been developed.

Project KME-506/518 Weldability limits for superalloy

Project leader: Lars Nyborg

The aim has been to establish a knowledge platform for assessment of weldability of Ni-based superalloys, with the limitation to develop a testing rationale that can be used to assess the overall weldability in a reliable way, to develop a reliable testing method (the Varestraint method) to assess susceptibility towards hot cracking, and to develop a testing rationale to assess the susceptibility towards strain age cracking.

The results show that different types of cracking and associated mechanisms may be active and interact at the same time and that the weldability concept needs to be evaluated in relation to specific welding processes concept since the cracking mechanisms may alter between these processes. When considering different alloys it is found that hot cracking susceptibility of Haynes 282 is less than that of ATI 718Plus and that ATI 718Plus liquates through constitutional liquation involving carbide phase. Insight regarding transformation characteristics of strengthening phases and the functions of different elements has also been obtained.

7 Industrial relevance – industrial results

The industry stakeholders participate actively in the project acquisition with own investments, as can be seen in section 5. The industry stakeholders have also participated and formulated project goals and content together with the research institutions. The expectations on results and its relevance are therefore high.

The industry stakeholders' confirmation on participation in the next programme period 2014-2018, in many cases at an increased level compared to previous stages, can also be interpreted as the stakeholders' expectations on the programme deliverables have been fulfilled. Furthermore, three new boiler manufactures have decided to participate in the next programme period.

In retrospect, the KME programme has contributed to significant knowledge and technological advancement within the field of material technology through the years, such as:

Initial tests with superheaters in sand seal for CFB boilers were started at KME (programme stage I). Valmet's (Metso) design of final superheater, placed in the cyclone seal in CFB boilers, has achieved technological advancement over the past five years. The discovery that resulted in this advancement is that the condensation of corrosive chloric alkali impurities on the surface of the superheater can be reduced significantly if the surface temperature is raised above a critical level. A new design with double pipes was developed and the temperature in the outer pipe was increased sufficiently to prevent condensation. The new discovery makes it possible to surpass the critical temperature window, which, in turn, permits still higher steam temperatures

Examples of directly usable results from completed projects in programme stage II are:

- useful knowledge gained directly through good test results, also in cases with less positive results.
- theoretical models for calculation and assessment of service life.
- documentation for assessment of material data and use of new materials.

The activities in stage III of the programme have essentially been oriented towards the problem of high temperature corrosion in superheaters in boilers for biofuel and waste. During the period a lot of attention was paid to the effect of chlorine to increase knowledge about corrosion caused by the chlorine content in the fuel.

This work has been taken further in stage IV, and according to Vattenfall, KME has made a large contribution to Vattenfall's work with its patented product ChlorOut, an additive that is added to the smoke gases to reduce corrosion and deposits in superheaters. The scientific and technological credibility of

Vattenfall's own work is strengthened by cooperation with KME, partly due to its explaining the mechanisms behind the additives and partly through its verification of ChlorOut's good results.

Apart from direct practical experience gained through operation and field trials, KME projects have generated a large number of scientific results for different temperatures and in different environments. This has been used to validate correlation and form models for the prediction of corrosion rates. Among other things, Valmet (Metso) has developed an advanced calculation model based on chemical equilibrium calculations for choice of materials in boilers.

A substantial part of KME's programme has been oriented towards the material development of gas turbine materials. See below for a number of examples that describe how various KME projects have contributed to increasing the competitiveness of gas and steam turbines developed and manufactured in Sweden.

- KME-projects on 9-12% Cr-steel have resulted in new steel alloys with improved corrosion resistance and better high temperature properties being introduced in both gas and steam turbines, which permits power stations with higher steam data. As example, materials are introduced in Siemens supercritical steam turbine for 620°C steam temperature.
- Service life models with the support of advanced trials is an area in which Siemens in Finspång has come a long way and is presently in front of many of its competitors. This development is fundamental to Siemens' ability to remain competitive in the development of new products and processes where optimal use of material is a prerequisite. Several KME projects at different institutions have made significant contributions to this development.
- KME projects on machining and residual stress in Inconel 718 have permitted costs savings that have improved the competitiveness of, for example, SGT-800.
- KME projects concerning TBC have played an important role in the ongoing process of introducing TBC coating on increasingly more products, which is a prerequisite for increased turbine temperatures and effectiveness.
- Reducing environments project, for development of combustion technology for increased fuel flexibility for the introduction of renewable fuels can result in reducing environments during combustion, which places special demands on materials.

Important work has been taken further into stage V, for example project on 9-12% Cr-steel and projects on TBC for continued and deeper studies. The implementation time of research is normally on 5-10 year horizon. However, the following examples of immediate results from programme stage V can be highlighted:

- Furnace wall corrosion has emerged as a significant problem with combustion of recycled wood and wood with refuse fractions. Projects within KME show that how furnace wall corrosion can be reduced with new coating and reduced boiler pressure.

- The effects of additives (waste products as sewage sludge) for reduction of corrosion have been studied. Preliminary results are promising.
- Plant owner have attained greater knowledge and basis for selection of a more cost effective superheater material. Promising new alumina forming materials, FeCrAl alloys, have been analysed in several environments and applications, and exhibit good potential for cost effective corrosion resistant material.
- Possibilities and challenges to construct a biofuel based CHP plant for 600°C steam temperature with increased electrical efficiency, have been studied and mapped. Greater knowledge and understanding how a plant can be designed, for example plant sizes and coupling of turbine and boiler, placing of superheaters and technical/economical optimization.

8 Evaluation

The programme was evaluated in April may 2013, by an international evaluation team with Ronny Nilsson as team leader, Henrik Gåverud as deputy team leader, and with Alina Agüero Bruna, Rudolph Blum and Carl-Johan Fogelholm as technical experts.

The evaluation covered both technical and scientific quality, industry relevance, goal achievements, dissemination of the results, programme governance etc.

The dominating overall conclusion was that KME is a successful well-functioning research programme with an obvious goal, active stakeholders and an administrative structure and function that has to be considered as very good. Furthermore it is obvious that KME contributes to integration between industry and universities in a very positive way. The research activities are in general on an excellent scientific level. Some of the projects are to be classified as top class researching projects in an international perspective, and projects will produce results with high industrial relevance.

9 Key figures and goal fulfilment

9.1 Examines

The following academic examines were concluded during 2010-2013:

Mattias Calmunger – lic dec 2013, KME-501

Daniel Leidermark – lic maj 2010, PhD dec 2011, KME-502

Mikael Segersäll – lic mars 2013, KME-502

Joel Andersson – PhD 2011, KME-506

Kang Yuan – lic feb 2013, KME-503

Niklas Israelsson - lic januari 2013

Peter Viklund, PhD 2013, KME-504/508

Yousef Alipour, lic june 2013, KME-508

9.2 Project reports and publications

In appendix the project summaries from concluded projects are reported. The reports can be downloaded from KME webpage or ordered from Elforsk www.elforsk.se. Publications from the projects are reported in section 11.

9.3 Goal fulfilment

The goal fulfilment was evaluated in the evaluation. In the programme period, ten goals have been identified, goals that constitute steps towards the fulfilment of the objective and long-term vision. Eight of the goals concern material technology issues. The goal fulfilment is considered to be very good, and relevant projects working on these issues were conducted. All goals but two were fulfilled.

The goal on integration with the international welding project Weldmat was not fulfilled, but it was beyond KME's influence since Weldmat has not started.

The other goal that was not fulfilled was the development of the reference power plant. The programme cannot demonstrate such plant, and the demonstration is subjected to a commercial decision at energy companies. However, KME has elaborated reference power plants and studied the prerequisites for a demonstration plant with advanced steam data. Candidates for hosting the demonstration was sought for and three potential candidates were identified: E.ON Climate & Renewables (100-200 MW_e condensing plant in Antwerp, Belgium), Falu Energi och Vatten (20 MW_e CHP plant in Falun) and Vattenfall (50-70 MW_e CHP plant in Uppsala).

As for integration between universities and industry it was concluded that KME contribute significantly to deeper cooperation between the participating industrial companies and universities.

It can be stated that the programme has contributed to increased knowledge regarding material process solutions suitable for high temperature applications such as in superheaters in biofuel-based boilers and in gas turbines. The evaluation state furthermore that the KME projects in general exhibit an excellent scientific level. Some of the projects are top class in an international perspective.

10 Economy

Table 4, Final programme budget in decided projects.

Programme budget:, [kSEK]	MAT BAS	EFF	Total:	Programme and project financing:		
				SEA	%	Industry
For projects	50 228	42 847	93 075	37 083	39,8%	55 992
Administration	3 061	4 139	7 200	2 869	39,8%	4 331
Associated professor*)	800	800	1 600	637	39,8%	963
Seminars, reports	400	400	800	319	39,8%	481
Programme evaluations	400	400	800	319	39,8%	481
Sum:	**54 889**	**48 586**	**103 475**	**41 227**	**39,8%**	**62 248**
Project decisions, [kSEK]:						
KME 501	605	6 377	6 982	2 782	39,8%	4 200
KME 502	12 467		12 467	4 967	39,8%	7 500
KME 503	2 327		2 327	927	39,8%	1 400
KME 504	2 294		2 294	914	39,8%	1 380
KME 505	1 995		1 995	795	39,8%	1 200
KME 506	9 459		9 459	3 769	39,8%	5 690
KME 507	5 486	997	6 483	2 583	39,8%	3 900
KME 508	7 012	4 568	11 580	4 611	39,8%	6 969
KME 509	2 493	997	3 491	1 391	39,8%	2 100
KME 510	3 325		3 325	1 325	39,8%	2 000
KME 511		1 733	1 733	693	40,0%	1 040
KME 512	582	2 635	3 217	1 282	39,9%	1 935
KME 514	628	1 883	2 511	1 004	40,0%	1 507
KME 515	183	117	300	119	39,5%	182
KME 518	158		158	63	39,9%	95
KME 519		1 929	1 929	767	39,8%	1 162
KME 520	1 214		1 214	486	40,0%	728
KME 521		1 673	1 673	669	40,0%	1 004
KME 601		4 300	4 300	0	0,0%	4 300
KME 607		4 825	4 825	1 930	40,0%	2 895
KME 608		1 750	1 750	700	40,0%	1 050
KME 609 (separate decision)		2 458	2 458	935	38,0%	1 523
Administration	4 661	5 739	10 400	5 789	55,7%	4 611
Tot. for projects [kSEK]:	**54 889**	**41 981**	**96 870**	**38 500**	39,7%	**58 372**
Remaining budget, [kSEK]:	**- 0**	**6 605**	**6 605**	**2 727**		**3 877**

Table 5, Industry contributions in decided projects

Company, [kSEK]	Siemens IT	Vattenfall	GKN (Volvo)	Sandvik HT	E.ON VS AB	E.ON C&R	Sandvik MT	Outokumpu	Dong Energy	Valmet (Metso)	Fortum	Energy comp	Total sum
Projects:													
KME 501 In kind							3 520						**3 520**
Cash							680						**680**
KME 502 In kind	7 500												**7 500**
Cash													**-**
KME 503 In kind	1 400												**1 400**
Cash													**-**
KME 504 In kind		1 200											**1 200**
Cash		180											**180**
KME 505 In kind	600			600									**1 200**
Cash													**-**
KME 506 In kind			5 690										**5 690**
Cash													**-**
KME 507 In kind		200		3 000	300					400			**3 900**
Cash													**-**
KME 508 In kind		4 800		300	200	180	360	360		500			**6 700**
Cash		240										29	**269**
KME 509 In kind					1 500					300			**1 800**
Cash												300	**300**
KME 510 In kind	1 200								800				**2 000**
Cash													**-**
KME 511 in kind									1 040				**1 040**
Cash													**-**
KME 512 In kind		1 235		40	75	75		60		100			**1 585**
Cash		350											**350**
KME 514 in kind											827		**827**
Cash											680		**680**
KME 515 in kind													**-**
Cash		182											**182**
KME 518 in kind			95										**95**
Cash													**-**
KME 519 in kind				1 162									**1 162**
Cash													**-**
KME 520 i kind	728												**728**
Cash													**-**
KME 521 i kind							1 004						**1 004**
Cash													**-**
KME 601 In kind	400	400			150	300				300	200		**1 750**
Cash		300			100					100	250	1 800	**2 550**
KME 607 In kind	2 895												**2 895**
Cash													**-**
KME 608 In kind					640	370	40						**1 050**
Cash													**-**
KME 609 In kind	290	733				500							**1 523**
Cash													**-**
Total in-kind	**15 013**	**8 568**	**5 785**	**5 102**	**2 865**	**1 425**	**4 924**	**420**	**1 840**	**1 600**	**1 027**	**-**	**48 569**
Total cash	**-**	**1 252**	**-**	**-**	**100**	**-**	**680**	**-**	**-**	**100**	**930**	**2 129**	**5 191**

11 Publications from projects within the 2010-2013 programme

KME-501

Journal papers

[1] Mattias Calmunger, Guocai Chai, Sten Johansson and Johan Moverare
Deformation and damage behaviours of austenitic alloys in the dynamic strain ageing regime
Conditionally accepted at Engineering Fracture Mechanics.

Conference Articles

[1] Mattias Calmunger, Guocai Chai, Sten Johansson and Johan Moverare
Mechanical Behaviours of Alloy 617 with Varied Strain Rate at High Tempera*tures*
THERMEC '2013, International Conference on Processing & Manufacturing of Advanced Materials. Processing, Fabrication, Properties, Applications. December 2-6, Las Vegas, USA, 2013.

[2] Mattias Calmunger, Guocai Chai, Sten Johansson and Johan Moverare
Influence of deformation rate on mechanical response of an AISI 316L austenitic stainless steel
THERMEC '2013, International Conference on Processing & Manufacturing of Advanced Materials. Processing, Fabrication, Properties, Applications. December 2-6, Las Vegas, USA, 2013.

[3] Mattias Calmunger, Guocai Chai, Sten Johansson and Johan Moverare
Damage and Fracture Behaviours in Aged Austenitic Materials During High-Temperature Slow Strain Rate Testing
Seventh International Conference on Materials Structure & Micromechanics of Fracture (MSMF7) 1-3 July 2013, Brno, Czech Republic, 2013. Key Engineering Materials, 2014, 592-593, 590-593.

[4] Mattias Calmunger, Ru Peng, Guocai Chai, Sten Johansson and Johan Moverare
Advanced Microstructure Studies of an Austenitic Material Using EBSD in Elevated Temperature In-Situ Tensile Testing in SEM
Seventh International Conference on Materials Structure & Micromechanics of Fracture (MSMF7), July 1-3, Brno, Czech Republic, 2013. Key Engineering Materials, 2014, 592-593, 497-500.

[5] Mattias Calmunger, Guocai Chai, Sten Johansson and Johan Moverare
Damage and Fracture Behaviours in Advanced Heat Resistant Materials During Slow Strain Rate Test at High Temperature
13th International Conference on Fracture (ICF13), June 16-21, Beijing, China, 2013.

[6] Mattias Calmunger, Guocai Chai, Sten Johansson and Johan Moverare
Influence of High Temperature Ageing on the Toughness of Advanced Heat

Resistant Materials
13th International Conference on Fracture (ICF13), June 16-21, Beijing, China, 2013.

[1] Mattias Calmunger, Guocai Chai, Sten Johansson and Johan Moverare
Influence of Dynamic Strain Ageing on Damage in Austenitic Stainless Steels
19th European Conference on Fracture (ECF19), Fracture Mechanics for Durability, Reliability and Safety, August 26-31 2012, Kazan, Russia, 2012.

[2] Mattias Calmunger, Guocai Chai, Sten Johansson and Johan Moverare
Long term high-temperature environmental effect on impact toughness in austenitic alloys
Accepted for presentation at the 13th International Conference on Fracture and Damage Mechanics (FDM13), 23-25 September, São Miguel Island, Portugal, 2014.

Licentiate Thesis

[1] Mattias Calmunger
High-Temperature Behaviour of Austenitic Alloys: Influence of Temperature and Strain Rate on Mechanical Properties and Microstructural Development
2013

KME-502

[1] Leidermark D, Moverare J, Simonsson K, Sjöström S. A combined critical plane and critical distance approach for predicting fatigue crack initiation in notched single-crystal superalloy components. Int J Fatigue 2011;33:1351–9.

[2] Leidermark D, Moverare JJ, Segersäll M, Simonsson K, Sjöström S, Johansson S. Evaluation of fatigue crack initiation in a notched singlecrystal superalloy component. Procedia Eng 2011;10:619–24.

[3] Kanesund J, Moverare J, Johansson S. The deformation and damage mechanisms during thermomechanical fatigue (TMF) in IN792. Procedia Eng 2011;10:189–94.

[4] Kanesund J, Moverare J, Johansson S. Deformation and damage mechanisms in IN792 during thermomechanical fatigue. Mater Sci Eng A 2011;528:4658–68.

[5] Sato A, Moverare J, Hasselqvist M, Reed R.C. On the Oxidation Resistance of Nickel-Based Superalloys. Adv Mater Res 2011;278:174– 9.

[6] Moverare J, Sato A, Johansson S, Hasselqvist M, Reed RC, Kanesund J, et al. On Localized Deformation and Recrystallization as Damage Mechanisms during Thermomechanical Fatigue of Single Crystal Nickel-Based Superalloys. Adv Mater Res 2011;278:357–62.

[7] Leidermark D. Crystal plasticity and crack initiation in a single-crystal nickel-base superalloy": Modelling, evaluation and applications. Dissertation, Linköping University Electronic Press, 2011.

[8] Reed RC, Moverare J, Sato A, Karlsson F, Hasselqvist M. A New Single Crystal Superalloy for Power Generation Applications. Conf: Superalloys2012, 2012, p. 197–204.

[9] Leidermark D, Aspenberg D, Gustafsson D, Moverare J, Simonsson K. The effect of random grain distributions on fatigue crack initiation in a notched coarse grained superalloy specimen. Comput Mater Sci 2012;51:273–80.

[10] Moverare JJ, Segersäll M, Sato A, Johansson S, Reed RC. Thermomechanical Fatigue of Single!Crystal Superalloys: Influence of Composition and Microstructure. Conf: Superalloys2012, 2012:369–77.

[11] Segersäll M, Moverare JJ, Simonsson K, Johansson S. Deformation and Damage Mechanisms During Thermomechanical Fatigue of a Singlecrystal Superalloy in the <001> AND <011> Directions. Conf: Superalloys2012, 2012, p. 215–23.

KME-503

Journal and Conference Articles

[1] K. Yuan, R. Eriksson, R. Lin Peng, X.-H. Li, S. Johansson, Y. Wang
MCrAlY Coating Design Based on Oxidation-Diffusion Modelling. Part I: Microstructural Evolution
Submitted to Surface and Coatings Technology. (2014).

[2] K. Yuan, R. Eriksson, R. Lin Peng, X.-H. Li, S. Johansson, Y. Wang
Modeling of microstructural evolution and lifetime prediction of MCrAlY coatings on nickel based superalloys during high temperature oxidation
Surface and Coatings Technology. 232 (2013) 204-215.

[3] K. Yuan, R. Lin Peng, X.-H. Li, S. Johansson, Y. Wang
Simulation of oxidation-nitridation-induced microstructural degradation in a cracked Ni-based superalloy at high temperature
EUROSUPERALLOYS 2014 (2014).

[4] K. Yuan, R. Lin Peng, X.-H. Li, S. Johansson, Y. Wang
Influence of Ru, Mo and Ir on the Behavior of Ni-Based MCrAlY Coatings in High Temperature Oxidation
ASME Turbo Expo 2014: Turbine Technical Conference and Exposition (2014).

[5] K. Yuan, R. Eriksson, R. Lin Peng, X.-H. Li, S. Johansson, Y. Wang
Interdiffusion and microstructure simulation in Ni and Co based overlay coatings on a Ni based superalloy at high temperatures
Thermec 2013 (2013).

[6] K. Yuan, R. Lin Peng, X.-H. Li, S. Johansson, Y. Wang
Analysis on microstructural evolution of PtAl diffusion coating on Ni-based superalloy influenced by creep process
The 4th Conference on the Integrity of High Temperature Welds & 9th International Conference on Creep and Fatigue (2012).

[7] K. Yuan, R. Lin Peng, X.-H. Li, S. Johansson, Y. Wang
Creep fracture mechanism of polycrystalline Ni-based superalloy with diffusion coatings
13th International Conference of Fracture (2013).

[8] K. Yuan, R. Lin Peng, X.-H. Li, S. Johansson
Influence of Precracked Diffusion Coating of Pt-Modified Aluminide on HCF Fracture Mechanism of IN-792 Nickel-Based Superalloy
Applied Mechanics and Materials. 148-149 (2011) 24-29.

[9] R. Eriksson, K. Yuan, X.-H. Li, R. Lin Peng
MCrAlY Coating Design Based on Oxidation-Diffusion Modelling. Part II: Lifing Aspects
Submitted to Surface and Coatings Technology. (2014).

[10] R. Eriksson, K. Yuan, S. Johansson, R. Lin-Peng
Internal oxidation of atmospheric plasma sprayed coatings
ASME Turbo Expo 2014 (2014).

[11] R. Eriksson, K. Yuan, S. Johansson, R. Lin Peng, X.-H. Li
Life prediction of high-temperature MCrAlY coatings based on microstructural observations
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Appendix Project summaries

Appendix Project summaries

Project KME-501 Long term high temperature behaviour of advanced heat resistant materials

Project leader: Sten Johansson, LiU

A worldwide increase in use of energy connected to an increase in carbon dioxide emission during combustion has increased the demand on energy producers and consumers to use more biomass fuels and also to increase efficiency by increasing temperature and pressure in energy conversion plants. This often leads to problems connected to materials properties. There is also a need for the future to introduce plants with the purpose of regulating the systems and compensate for fluctuations caused by weather based energy production like solar and wind energy with a large number of start and stop cycles. This is increasing the need for new testing methods taking into account variation in temperature and load. This together with the trend of increasing temperature and corrosiveness in the environment means a demand for new austenitic materials improved by higher Ni-content and other minor additions alloying elements. This in turn leads to a need for increased knowledge about how of deformation mechanisms not so often accounted for like twin formation can be better understood and used to improve material properties.

In this project, the influence of low deformation rate at high temperatures on deformation, damage development and fracture properties are studied. Couplings to the development of microstructure has been investigated, resulting in an increased understanding of how strength and ductility are affected. Despite the fact that the plastic deformation is generally dislocation induced, other phenomena like dynamic strain ageing (DSA), twin induced plasticity (TWIP) and different precipitation phenomena are also acting. Those phenomena can lead to both improvements and deterioration of the performance of the materials depending on how they combine, so increased knowledge in this area is important. As soon as the influence of alloying and treatment on these phenomena is wholly understood new materials with better properties can be developed.

The goal fulfilment is high and above expectations due to the use of the modern metallographic methods EDSD and ECCI.

The cooperation with the industry partner is to be considered extremely good and The number of publications produced within the frame of this project is eight.

Keywords: Dynamic strain ageing, biomass power plant, austenitic stainless steel, twins, damage.

Project KME-502 Fatigue in nickel-based superalloys under LCF and TMF condition

Project leader: Johan Moverare, LiU

Improved knowledge regarding the mechanisms that govern crack initiationand propagation under service like conditions are important for the validation of advanced materials optimized for efficiency and robustness of the next generation of gas turbines. Within this project mechanical testing and microstructural investigations of deformation and damage have been combined with modelling efforts in order to characterize fatigue in nickelbased superalloys under LCF and TMF conditions. The project has been conducted in collaboration between the divisions of Engineering Materials and Solid Mechanics at Linköping University and Siemens Industrial Turbomachinery AB in Finspång.

Single crystal superalloys are highly anisotropic materials and they also display a tension/compression asymmetry under certain conditions. At low and intermediate temperatures the 〈111〉 direction shows the highest elastic modulus and the lowest yield strength. Also at low and intermediate temperature the Tensile/Compression asymmetry is very pronounced but only for the 〈011〉 direction which is stronger in compression than in tension. The 〈011〉 direction is also odd in the sense that it shows a very strong tendency for serrated yielding during deformation which seems to lower the fatigue life. The deformation hardening rate also differ between the different directions; especially the 〈111〉 direction show a strong cyclic hardening during low cycle fatigue at 500°C. At higher temperatures where creep is significant one can again see that the 〈111〉 direction is the weakest direction but this time a pronounced Tension/Compression asymmetry is found in the creep relaxation behaviour for the 〈001〉 direction which is stronger in tension than in compression.

The deformation behaviour is often very localized in single crystal materials and the formation of twins is an important deformation mechanism. This localization has been found to be very important for the accumulation damage which eventually will lead to fatigue failure. Our study have shown that also the formation of twins during thermomechanical fatigue differ for different directions. The twin formation typically occurs in compression or during OP TMF testing for the 〈001〉 direction while for the 〈011〉 direction twin formation is mainly observed during tensile loading or IP TMF testing. Fundamental understanding of single crystal materials and their mechanical properties, including anisotropy, tension/compression asymmetry and localized deformation, has contributed to validate the use of single crystal materials in industrial gasturbines. Furthermore the project has given useful input to the development of the new single crystal material STAL15. An alloy which is aimed to better fulfil the requirements regarding fuel flexibility and cyclic operation in future gasturbines. It can therefore be claimed that the initial goals set up in the project have been fulfilled.

Keywords: Thermomechanical fatigue, Creep, Single crystals, Superalloys

Project KME-503 New Durable MCrAlX Coatings for High Temperature and Corrosive Environment Applications in Advanced Engines

Project leader: Ru Lin Peng, LiU

The development of coatings providing better oxidation and corrosion protection for hot components in engines is highly needed by the energy production industry to meet the increased gas turbine operation requirements. Such coatings may promise increased gas turbine availability, operation flexibility and improved engine efficiency. MCrAlY (M: Ni and/or Co) are widely used as overlays or bondcoats in thermal barrier coating (TBC) systems to protect superalloys operated in the hot sections of gas turbines or jet engines. Increased understanding of the behavior of different elements in the MCrAlY coatings and recognition of increased requirements for applications in the land based gas turbines reveal that further improvement of MCrAlY coatings is not only possible but also important.

The aim of this project is to develop new durable MCrAlX (X: alloying elements of minor addition) optimised for the operation conditions in land based gas turbines of medium size (10-60 MW). Such gas turbines operate are used for both base load (long loading duration at high temperatures and few cycles) and peak load (frequent cycles) operations; thus it is important that the coating can resist both long term oxidation and thermal cycling. Systematic work integrating thermodynamic modelling and experimental studies are carried out to refine the chemical compositions with regards to resistance against oxidation, thermal cycling and corrosion. The mechanisms of coating degradation during exposure to high temperature and thermal cycling and the influence of the coating composition are investigated by experiment and simulation. Mechanical properties are also characterized by adhesion test and hardness measurement.

The research work has been carried out through close cooperation between the Division of Engineering Materials of Linköping University and Siemens Industrial Turbomachinery in Finspång. The joint efforts have led to the following main achievements which are listed to match the four goals set up in the project application: (1) One Ni based and one Co based MCrAlX with promising performance have been identified and patented; (2) An oxidation-diffusion model, considering surface oxidation, coating-substrate interdiffusion and structural hinders for diffusion, has been developed and coating property data have been generated by the different characterization tests and analyses; (3) Twelve scientific papers have been published or submitted under the project period, with 8 of them directly from the project and the rest partly related to the project; (4) A licentiate thesis was presented early 2013 and a PhD dissertation is planned for the autumn of 2014. Planned DBTT and ductility tests of selected coatings, which are part of the characterization experiments related to goal (2), remain to be done. Otherwise, all the project goals are fulfilled.

Tests to further characterize the coatings' application properties and for coating qualification are to be carried out in phase II through the planned continuation project. The eventual application of the coatings in the target gas turbines is expected to provide better protection for certain hot components and thus contribute to better gas turbine performance.

Key words: MCrAlX coatings, oxidation, thermal cycling, corrosion, thermodynamic modelling, diffusion modelling

Project KME-504 Correlation between deposit chemistry and initial corrosion of superheaters

Project leader: Rikard Norling

Biomass generally contains high amounts of potassium and chlorine, while the content of sulphur is normally relatively low. During combustion these elements are released to the flue gas forming various aggressive species that can severely accelerate the corrosion attack. One strategy to avoid corrosion problems is to change the atmosphere in the boiler. It has been proven that deposit formation and superheater corrosion can be counteracted by co-combustion with sulphur-rich fuels or additives. Sludge often contain high amount of phosphates, which are believed to have a similar effect on the gas phase reactions as sulphates. Extensive research on laboratory scale in recent years has surely contributed to an increased understanding of the corrosion problem of superheater tubes. However, laboratory exposures do not take the complex environment with numerous competing reactions in to account.

In this project, complex, yet controlled, pilotscale exposures have been performed to further increase the knowledge regarding superheater corrosion. The main focus in the project has been to analyse deposits and materials from pilot-scale tests, using controlled dosage of S and P. Tests have also been performed and compared with samples from full scale testing. The goal with the project was to increase the detailed knowledge and understanding regarding the effect of increased steam temperatures and the controlled use of additives on deposit formation and initial corrosion of superheater tubes. A secondary objective was to establish a guideline for deposit and corrosion analysis method.

The work has been carried out by Vattenfall AB, Swerea KIMAB and SP Technical Research Institute of Sweden during the period 2010-2013.

The result from the project showed that by increasing the dosage of both sulphur and phosphor containing additives the alkali chloride content in the flue gas could be decreases and it was also shown that phosphorous containing additive have the best effect (measured in kg, P or S/h/MW) compared to the sulphur containing additive. However, for MAP a higher addition was needed compared to AS in order to decrease the chloride content in the deposit, while for AS lesser amount of additive was required to do this effectively. Another factor that also showed to affect both the KCl (g) in the flue gas and the chlorine content in the deposit in a positive way was the oxygen content (λ). A better sulphation of the flue gas could consequently be achieved by using both increased sulphate injection rates and increased excess air ratios.

When studying the samples and deposits in cross section it could be seen that both additives decreased the chlorine close to the metal/oxide interface. Instead low amounts of sulphur could be detected which indicates that the deposited KCl (s) is sulphated before the chlorine can diffuse through the oxide scale or that sufficient sulphation also is occurring close to the interface.

The initial corrosion was shown to increase with higher KCl (g) in the flue gas. However, an increase in sulphur addition and oxygen level seemed to decrease the risk of corrosion. The investigation showed that the used additives seemed to have a slight effect of the initial corrosion although it was not very pronounced. It was shown that the local corrosion attacks occurring for all samples played an important role in the evaluation. Sulphate addition was also shown to decrease the risk for internal corrosion at the higher temperatures.

To establish schemes for controlled dosage of additives proved to be difficult in particular for ammonium sulphate. In fact, during injection the exact dosage was shown to be of lesser importance than the excess air ratio for the studied conditions. This information is highly valuable though, since the excess air ratio is typically decided from other criteria than corrosion, such as economic.

The project goals have been fulfilled and increased knowledge and understanding regarding the deposit formation and initial corrosion in different atmospheres has been achieved. The secondary objective, to establish a guideline for deposit and corrosion analysis has also been fulfilled. All investigated analysis techniques were shown to be useful and knowledge about time and cost for the different techniques has been achieved.

Keywords: Waste wood, biomass, corrosion, chlorine, sulphur, phosphor, analysis methods, stainless steel

Project KME-505 Properties of alloyed MoSi2 matrix composite for hot corrosion and elevated temperature components of gas turbine

Project leader: Yiming Yao

In the light of increased gas turbine efficiency and minimised hazardous emission of future biomass-fuelled energy converting system, industries are constantly looking forward to high temperature ceramics and intermetallics to replace conventional materials. $MoSi_2$-based composite is one of the candidates due to its higher temperature capability and oxidation resistance superior to superalloys. The goal of our investigation is to find the application of $MoSi_2$-based materials in the high power-to-heat ratio biomass power generation systems. Our KME-405 project has evidenced that $(Mo_{0.9}Cr_{0.1})Si_2$ +15vol% ZrO_2 composite has high oxidation resistance at 1400°C and remarkable sinterability, and we have developed ceramic manufacturing method of mixing/granulation - CIP – pre-sintering – CNC matching – pressure-less sintering (PLS) to produce a prototype of SGT800B turbine heat shield.

The project KME-505 aimed at the evaluation of mechanical and thermal cycle fatigue properties of the Cr-alloyed composite compared with commercial candidate materials (e.g. Si_3N_4). Physical properties of the material were measured, since these data are required for component design. Investigations have been carried out on Cr-alloyed composite $(Mo_{0.9}Cr_{0.1})Si_2$+15 vol% ZrO_2 and un-alloyed composite $MoSi_2$ +15 vol% ZrO_2. KME-505 project was supported by two industrial companies and a university: Sandvik Materials Technology (Kanthal) as material manufacturer; Siemens Industrial Turbomachinery AB as end-user of the materials; and Chalmers University of Technology.

4-point bending tests resulted in a fracture strength for $(Mo_{0.9}Cr_{0.1})Si_2$+15 vol% ZrO_2 of 200 and 320 MPa at 1200°C and RT, respectively. Room temperature fracture toughness was 4.7 $MPa{\cdot}m^{1/2}$, measured with standard 4-point SEVNB method. Hardness (HV10) was 8.2 GPa The mechanical properties of the Cr alloyed composite are close to published data of similar materials. As-sintered +15 vol% ZrO_2 displays parabolic weight gain in isothermal oxidation exposures at 1000 – 1500°C for 1000 h. However, this composite exhibited degraded performance in thermal cycling exposures (TFC) at 1200 and 1300°C, which was possibly attributed to martinsite phase transformation of ZrO_2 at lower temperature than DBT of the silicide, and the reduced E modulus in the Cr-alloyed matrix. The composite $(Mo_{0.94}Cr_{0.06})Si_2$+15 vol% ZrO_2 with lower Cr addition showed promising properties in both isothermal and cyclic testing. On the other hand, excellent HT oxidation and thermal cyclic resistance of $MoSi_2$+15 vol% ZrO_2 composite has been proved in the same tests, being comparable to that of monolithic $MoSi_2$. These intrinsic properties are, yet, influenced by a Si depleted Mo-Zr-Si silicide layer (~ 80 µm) on the as-sintered surface formed by the reduction by the sintering gas. The Mo-Zr-Si silicide layer at as-sintered surface is very brittle and leads to porous surface, which gives detrimental effects on HT oxidation and HT mechanical properties.

It is concluded through KME-505: (1) As-sintered $(Mo_{0.9}Cr_{0.1})Si_2$+15 vol% ZrO_2 composite produced by PLS has moderate strength at 1200°C and fracture toughness at room temperature. It can be used with low loading in isothermal condition in oxidizing environments up to 1500°C, but is not suitable in cyclic oxidation conditions. (2) Alloyed silicide matrix composite with a lower Cr addition is very promising to compromise the alloying effect on sintered surface and bulk. (3) $MoSi_2$+15 vol% ZrO_2 possesses excellent intrinsic oxidation resistance up to 1500°C and thermal cyclic oxidation resistance up to 1300°C. The bulk of this composite is suitable for high temperature components used at cyclic oxidation conditions, but the detrimental Si-depleted silicide formed at $MoSi_2$+15 vol% ZrO_2 surface has to be avoided. The possible solution could be adjustment of oxygen content in the sintering gas, and applying suitable pre-oxidation post sintering treatment.

According to the results of KME-505, it is advisable to focus the activity on lowering the Cr addition in $MoSi_2$ matrix, and tailoring the sintered surface of $MoSi_2$ + 15 vol% ZrO_2. The achieved technique can be applied to the development of related $MoSi_2$ based materials produced by PLS technique.

Keywords: molybdenum disilicide, composite, mechanical testing, thermal cyclic fatigue, high temperature oxidation, hot corrosion.

Project KME-506/518 Weldability limits for superalloy

Project leader: Lars Nyborg

The aim has been to the establish knowledge platform for assessment of weldability of Ni-based superalloys. This aim has been limited to a number of selected the objectives, namely: to develop a testing rationale that can be used to assess the overall weldability in a reliable way; to develop a reliable testing method (the Varestraint method) to assess susceptibility towards hot cracking; the develop a testing rationale to assess the susceptibility towards strain age cracking.

The projects (KME 506 and KME 518) have been based on cooperation in between Chalmers University of Technology and GKN Aerospace Sweden AB, but also led to extensive international co-operation with in particular University of Manitoba, Canada. Major work has been done within KME506. The latter much smaller project (KME518) has in particular been connected to internationalisation activities. The reference group has included local participants and an external member at Siemens. The so-called Varestraint testing method has been facilitated and equipment for this has been built and developed. By also using Gleeble testing (Univ. Manitoba), thermodynamics and kinetics modelling (JMatPro), thermal analysis (DTA/DSC) and electron microscopic studies, an extensive assessment of the weldability of a number of important superalloys has then been realised.

In short, the results show that different types of cracking and associated mechanisms may be active and interact at the same time and that the weldability concept needs to be evaluated in relation to specific welding processes concept since the cracking mechanisms may alter between these processes. Hence, a systematic integrated procedure is suggested to assess weldability in a consistent and cost effective way.

When considering different alloys it is then found that hot cracking susceptibility of Haynes® 282® is less than that of ATI 718Plus® and that ATI 718Plus® liquates through constitutional liquation of NbC. Hence, a hypothesis regarding liquation of MoC through eutectic transformation of Ni-Mo or Ni-Mo-S in Haynes® 282® is possible. Here, insight regarding transformation characteristics of strengthening phases and the functions of different elements has been obtained using JMatPro and DTA/DSC.

The goal fulfilment is considered to be more than complete with respect to the overall goal of finding specific superalloy combinations, welding methods and appropriate heat treatment schedules to increase the potential for hot gas turbine structures applications, including measurable achievements as follows: The design and building of a Varestraint testing machine; the development of anew testing approach for strain age cracking; the weldability assessment of different superalloys; the completion of more than 20 diploma thesis studies, the submission/publication of 19 papers; the eatablishment of a international network with leading scientists in Canada and Finland. Also, in addition a sub-project within the Clean Sky programme has been granted and run as a result.

Keywords: welding, nickel-base superalloys, testing methods, hot cracking, strain age cracking

Project KMME-507 FeCrAl alloys as components in biomass- and waste- fired boilers

Project leader: Kristina Hellström

Characteristic of superheater corrosion in biomass- and waste- fired boilers is the combination of relatively low metal temperatures and chemically aggressive environment. The materials conventionally used in such highly corrosive applications are predominantly chromium oxide forming material. Work in HTC has shown that certain chemical reactions, especially the formation of alkali chromate (VI), which depletes the protective oxide in chromium and tends to transform the oxide into poorly protective iron oxide which can lead to a sudden increase in the corrosion rate (breakaway corrosion). One possible strategy to avoid this problem would be to use a completely different type of material that forms a protective oxide layer that is not attacked by alkali in the interesting temperature range. An alternative would be to use the alumina forming alloys, such as the familiar FeCrAl steels in these environments. The usefulness of the group FeCrAl alloys is based on the formation of a slow growing and highly protective Al2O3 layer on the material surface. However, the usefulness of alumina formers is questionable at temperatures typical of the superheaters (< 600 °C). This is mainly due to the slow diffusion of aluminum in the alloy at these temperatures. Replacing the alloys currently used in these applications with more corrosion resistant alloys may make it possible to design new facilities for higher steam temperatures, and thus get more "green" electricity per unit of fuel.

This project investigated the usefulness of iron-chromium-aluminium alloys in waste- and biomass- fired boilers. In the laboratory, it was examined if an Al2O3 surface layer, established by pre-oxidation, can protect the material during exposure in a boiler environment. A FeCrAl material, Kanthal® APMT, with and without an Al2O3 layer was then exposed in the field together with a reference material, Sanicro 28, on a corrosion probe at 600 and 700 °C for 24-1000 hours. Also, uncooled non pre-oxidized APMT and Inconel 625 were exposed at a range of temperatures (350-900 °C). The materials were then analyzed with respect to loss of material and corrosion products.

The laboratory investigations show that a thicker alumina surface layer stays intact for a longer time than a thinner but eventually spalls off. The spallation is initiated by oxide formation at defects. Together with the accompanying volume expansion and alloy chlorination, the spallation spreads over the surface. In the probe exposure alloy APMT showed by far the best ability to withstand corrosion. The metal loss of the chromia forming Sanicro28 was more than twice that of Kanthal APMT at 600°C and 700°C. Surprisingly, the metal loss was higher on the pre-oxidized material. These results are in line with results from KME 414. Also the uncooled material test (350-700°C) show that Kanthal APMT manages a waste fired environment better than the chromia forming Inconel 625. At the higher temperatures more exposures are needed to draw any conclusions.

The results show that the corrosion resistance of certain components of the waste-fired boilers can be improved significantly if the existing material is replaced with FeCrAl material, such as thermo shield tubes and superheaters (as coatings due to the pressure load). The surprising result that the pre-oxidation is not favorable when the material is used at temperatures below 700°C means that production of major boiler components in FeCrAl material would be greatly facilitated.

Keywords: FeCrAl alloy, pre-oxidation, superheater, alumina, alkali salt.

Project KME-508 Furnace wall corrosion in biomass-fired boilers at higher steam temperatures and pressures

Project leader: Pamela Henderson

Wider use of low quality fuels like waste wood (demolition wood), in combination with the requirements of reduced NOx emissions, makes it much more difficult to avoid corrosion in reducing atmospheres adjacent to the furnace walls (water walls). Waste wood has a high content of alkali metals and chlorine, as well as heavy metals like lead and zinc, which increases the risk for corrosion. As a result, furnace wall corrosion is already a major problem in combined heat and power plant burning waste wood, especially at high steam pressures like 140 bar. Corrosion rates of up to 1.5 mm a year have been measured on low-alloy steel furnace walls giving a lifetime of only 3 years if no action is taken. A new furnace wall for a 100MWth boiler can cost SEK 20 million.

Most corrosion research is performed in the laboratory under simulated boiler conditions, but there is also a need to perform corrosion and deposit tests in real boilers. There is a need for long-term corrosion tests at the furnace walls on different material coatings at different temperatures. The use of additives and other methods for reducing wall corrosion should be considered. These needs have been addressed in the present project which has the goal to give recommendations regarding how to avoid water wall corrosion at high boiler electrical efficiency/ steam data.

The target group for this research includes power producers, boiler manufacturers and material suppliers and it is this constellation, together with institutes and a university that have performed the project.

The results showed that coating the low alloy steel (16Mo3) furnace wall tubes with a nickel base alloy (Alloy 625) drastically reduced the corrosion rate. An FeCrAl (Kanthal - APMT) alloy containing 21%Cr also showed low corrosion rates. This alloy was found to be susceptible to embrittlement in the temperature range of service, 400-500°C, but FeCrAl alloys with Cr contents of about 10% were not embrittled and should be evaluated in the future. Austenitic stainless steels like TP310, San 28, 153 MA and 253MA showed moderate corrosion rates and could be an alternative to Ni-base alloys for protecting furnace walls.

The method of applying the coating was found to be important. In general, the thermally sprayed coatings did not adhere as well as the weld overlay coatings.

The nickel alloy coated tubes and probe samples were attacked by a potassium-lead combination leading to the formation of non-protective potassium lead chromate. The low alloy steel tubes and probe samples corroded by Cl attack and K and Pb were not found at the corrosion front. Initial results from examination of a FIB –produced section showed that iron chloride formed as a distinct layer under the oxide and oxy-chlorides were not detected. The corrosion rate of 16Mo3 was highly temperature dependent.

The Kanthal FeCrAl alloy was also attacked by chlorides, although this alloy showed very low corrosion rates. Stainless steels were attacked by a combination of chlorides and potassium-lead.

Preliminary results from the use of digested sewage sludge which was mixed with the waste wood indicated that levels of Pb, K, Na and Cl were reduced on the furnace wall deposits. This led to a reduction in the corrosion rate during short-term tests and suppressed the formation of potassium-lead chromate in Alloy 625 as the protective chromia layer was maintained. This sludge could be a useful means of reducing corrosion and should be further investigated.

Thermocalc modelling showed that HCl(g) is favoured over Cl_2(g) as the corrosive species. The initial work with Thermocalc showed that many of the phases formed by the corrosive environment could be predicted.

Thermodynamic modelling of phases expected in the flue gases using HSC-Chemistry and SteaMax (based on FACTData) showed that the reducing conditions cases were characterized in a similar way by both calculation tools. The results were in broad agreement with the composition of the deposits collected from the walls of the Idbäcken boiler.

Initial experiments with GD-OES and FIB- instruments showed that these were useful for preparing or analysing the corrosion front and should be used more in the future to facilitate more precise mechanistic studies.

The novel aspects from this work include :-

- the use of long-term testing of probes at the furnace wall in real boiler environments,
- evaluation of FeCrAl alloys for use on furnace walls,
- identification of potassium and lead in combination as participants in the corrosion process for Ni-base alloys
- the use of treated sewage sludge as an additive which prevented the attack of chromia by potassium and lead to form chromate, resulting in a reduction in the corrosion rate
- showing that HCl(g) is favoured over Cl_2(g) as the corrosive species for iron-based alloys
- use of FIB and GD-OES instruments on samples exposed in boilers

The results of this project can be utilised by the power industry to reduce furnace wall corrosion. For example, furnace walls have already been overlay welded with Alloy 625.

The goal of the project was to give recommendations on how to how to avoid water wall corrosion at high boiler electrical efficiency/ steam data, which has been fulfilled.

Keywords: waste wood, corrosion, furnace walls, steels, Ni-base alloys

Project KME-509 Improved determination of service life of superheaters in boilers burning biomass and waste

Project leader: Jesper Liske

The main aim of this project has been to improve the plant economy by generating fundamental knowledge about how probe exposures can be used in order to estimate the lifetime of the superheater. The corrosion rate obtained from the probe exposures usually exaggerates the actual corrosion rate of the superheaters. The reason for this is probably related to several parameters, of which this project has aimed to investigate the effect of start-up, the effect of exposure time and if there is any inherent difference between probe and tube exposures. The knowledge generated within the project is beneficial to several actors within the power industry, e.g. boiler owners, boiler manufacturers and materials producers.

The project has successfully executed a comprehensive exposure matrix in the waste fired boiler (P14) at Händelöverket, Norrköping. This includes 5 probe exposures and 6 test sections in the existing superheater exposed in time resolved manner up to 5600 hours. The exposure matrix contained 6 different materials exposed at two different material temperatures, where corrosion rates were obtained for materials at the existing material temperature of today's superheaters as well as a temperature aimed at future boilers with higher steam data.

The results show that corrosion rates of the probe exposed samples are generally low, which is consistent with the corrosion rate measured on the existing superheaters (the current lifetime is 12 years). The corrosion rate of Sanicro28, exposed on the probes had basically the same corrosion rate as the Sanicro28 currently installed in the superheater, 0.02 mm/year and 0.03 mm/year, respectively. The corrosion rate increased for two of the three materials investigated when the material temperature was increased from 420 °C (existing superheater material temperature) to 500 °C. For Sanicro28 exposed at 500 °C, the corrosion rate was 0.3 mm/year.

The project also investigated if there was any inherent difference between the corrosion rate of probe exposed samples and the superheaters. According to the results, it does not seem to exist such a difference. Hence, probe exposures are a possible way of investigating the potential corrosion rate of superheaters. However, it is important to stress that the probe exposures needs to, as far as possible, mimic the thermal and environmental history of the superheater. This includes for instance how the probe exposures are started and handling during shorter stops. The results indicate that a startup with cold probes directly into a hot boiler affect corrosion attack negatively.

In summary, the project has demonstrated how corrosion rates change over time, the importance of having the probe exposures mimicking the thermal and environmental history of the superheaters, compared the corrosion rate at the existing temperature and at an elevated temperature, 80 ° C higher than the existing one. The conclusion is that probe exposures can be used for estimating the potential corrosion rate of superheaters.

Keywords: probe exposures, corrosion rate determination, corrosion in waste fired boilers

Project KME-510 New Martensitic Steels for Steam Power Plants with Higher Efficiency

Project leader: Hans-Olof Andrén/Fang Liu, Chalmers

The thermal efficiency of steam power plants is limited by the maximum allowed steam temperature and pressure, which in turn are determined by the corrosion and creep resistance of available steels. All attempts so far to exceed 600-620°C with 11-12% chromium steels have failed, and we now know that the reason is the precipitation of a complex nitride, Z-phase, after a few years of service. This phase is coarse and grows at the expense of fine VN precipitates, leading to a dramatic fall in creep strength. This project aims at developing a new generation of martensitic chromium steels that use Zphase as a strengthening rather than weakening phase. The new steels have the potential to be used as piping or superheater tubing in future biomass power plants with increased operation temperature.

The close collaboration between Chalmers University of Technology, Siemens Industrial Turbomachinery AB, and DTU/DONG Energy has led to fundamental knowledge gained on the new Z-phase strengthened steels. The efficient exchange of information within the essential feedback loop between alloy designing, microstructure analyses, and mechanical testing have resulted in a deep understanding of the system.

We have proved that the concept of using fine and densely distributed Zphase to strengthen 12% chromium steel is feasible. Despite their much higher chromium content the proof-of-concept alloys showed excellent creep resistance, comparable with benchmark alloys.

Further fine tune of the alloy chemical composition were performed to address two issues: firstly to improve the room temperature impact toughness of the proof-of-concept alloy; secondly to introduce a “normal” amount of carbon into the alloy and make the future implementation of the alloy more economically viable. Significant improvement in toughness has been achieved. However, slightly compromised creep strength was found in the newly designed alloys.

The goal set for the project has been successfully fulfilled.

Keywords: 12% Cr steels, Z-phase strengthening, creep resistance, microstructure

Project KME-511 Critical corrosion phenomena in power generation from biomass – Identification of chlorine resistant high temperature coatings/materials

Project leader: Torbjörn Jonsson, Chalmers

Alkali chloride induced corrosion is a key obstacle in KMEs goal of reaching a steam temperature of 600°C on wood-fired boilers, since alkali chloride induced corrosion has been identified as a limiting factor in these boilers. One way to potentially overcome this problem is to use corrosion resistant coatings/materials. In the present project superheater samples from a biomass fired boiler have been investigated, thermodynamic calculations and screening experiments have been performed in order to identify a possible corrosion resistant coatings. The most promising system (Ni-Al) has in addition been investigated through lab exposures.

Characterization of TP347HFG superheater samples revealed that the steel was not able to form a protective chromia scale under the superheater service conditions and long exposure times. Instead of protective chromium rich scale an outward grown iron rich oxide with a FeCrNi oxide beneath was formed on all samples. Along grain boundaries extensive attack was observed with both K and Cl present and presumably both being active in the corrosion process. The results from the detailed investigation of field samples were combined with thermodynamic calculations in order to select the most promising coating material. Thermodynamic evaluations using Thermo-Calc and screening experiments were used and the Ni-Al system showed largest potential and specifically the Ni_2Al_3 intermetallic phase that was selected for tests. Aluminised samples were produced at DTU using pack cementation. The aluminising led to formation of a ~30 µm thick layer of Ni_2Al_3.

The Al-Ni system was in addition investigated and compared with a traditional 18-8 stainless steel (304L) through lab exposures. It shows a large potential to form a protective scale in the alkali chloride environment used in the lab. The results have generated an interest among boiler owners and there are expectations to test the Ni-Al system in boilers. The goal with the project has thereby been fulfilled.

Keywords: Alkali chlorine induced corrosion, corrosion resistant coatings/materials, superheater lifetime

Project KME-512 Fuel additives to reduce corrosion at elevated steam data in biomass boiler

Project leader: Annika Stålenheim/Maria Jonsson, Vattenfall

Wide fuel mixes are of interest for many energy companies due to increasing prices and reduced availability of clean biomass. However, wide fuel mixes, including for example waste wood (demolition wood, recycled wood) contain components causing corrosion in the furnace and convective superheaters. Especially wall corrosion is a problem in plants that operate today at conventional / commercial steam data levels. Therefore, to be able to increase the steam data level in a demonstration plant, which is one goal for the KME programme in the period 2010-2013, it must be shown that the corrosion can be limited to levels that allow cost-effective operation.

There is little information available on the use of additives or fuel blends to reduce furnace wall corrosion. Recent Värmeforsk studies on wall corrosion have mainly evaluated different materials. Other KME projects (for example, KME-508) touch on the area of additives, but fuel additives are not their main focus. Thus, there is a need to focus more strongly on the use of additives within KME. Also, it would be useful to identify additives that reduce furnace wall and superheater corrosion.

The project goals have been fulfilled by the following achievements:

The project has identified four different types of additives that might reduce furnace corrosion. Five additives, representing these types were then selected and tested in a fluidised bed combustion test rig. As a result of these tests, two additives, digested sewage sludge and kaolin, were found to have a positive effect on waterwall corrosion as well as on superheater corrosion when burning waste wood.

Two additives have been found to be promising for reducing waterwall corrosion, sewage sludge and kaolin. These additives are also expected to reduce superheater corrosion, reduce the risk for bed sintering and reduce the amount of deposits on superheaters and economiser. The high ash content of sewage sludge will result in an increase in the amount of ashes. Addition of sewage sludge may increase the need for sulphur reduction in the flue gas cleaning to avoid exceeding SO_2 emission limits. The use of kaolin is expected to reduce superheater corrosion. It may also reduce the risk for bed sintering and reduce the amount of deposits on superheaters and economiser.

The project recommends that sewage sludge and kaolin (or some other aluminium silicate) should be further investigated for reduction of waterwall corrosion.

Thermodynamic equilibration calculations have been found to be a useful tool for predicting the effects of additives and variations in operation parameters in a boiler. However, this is a tool that must be used with some care and expert knowledge is needed for the interpretation.

Key words: furnace wall corrosion, superheater corrosion, additives to fuel

Project KME-514 Increased electrical efficiency and service life assessment of super heaters from combustion of difficult fuels

Project leader: Jesper Liske, Chalmers

The main aim of this project has been to improve the plant economy by generating fundamental knowledge about how probe exposures can be used in order to estimate the lifetime of the superheater. The corrosion rate obtained from the probe exposures usually exaggerates the actual corrosion rate of the superheaters. This aim has also been addressed by KME509 and by performing similar exposures in two boilers the results will be more general in character. The knowledge generated within the project is beneficial to several actors within the power industry, e.g. boiler owners, boiler manufacturers and materials producers.

The project has successfully executed a comprehensive exposure matrix including 12 probe exposures and 2 test sections in the existing superheater exposed in time resolved manner up to 3600 hours. Of the 12 probe exposures, 6 were of short term character (i.e. 4 hours) investigating the deposit formation. The exposure matrix included 3 materials and 2 material temperatures, performed at two positions in the superheater bundle. The two temperatures were chosen so that corrosion issues at current as well as future steam temperatures were investigated.

The results show that corrosion rates of the exposed probe samples (T22, 304L and 347H) are generally low, which is consistent with the corrosion rate measured at the existing superheater 2 bundle (the current lifetime is nearly 14 years). Even though the corrosion rate was similar, the corrosion morphology of the T22 and 304L samples were different. In the case of 304L, the corrosion attack was localized whereas for T22 the attack was of more general nature. It is suggested that this is due to the start-up sequence of the probes; being pre-oxidized in a mild environment during boiler start after revision.

The project also investigated if there was any inherent difference between the corrosion rate of probe exposed samples and the superheaters. According to the results, it does not seem to exist such a difference. Hence, probe exposures are a possible way of investigating the potential corrosion rate of superheaters. However, it is important to stress that the probe exposures needs to, as far as possible, mimic the thermal and environmental history of the superheater. The results indicate that a startup with cold probes directly into a hot boiler affect corrosion attack negatively.

In summary, the project has investigated how probe exposures and tube exposures correlate and how the corrosion rates change over time. This has been done at two positions at SH2 and at current superheater temperature as well as an increased temperature. In addition, the deposit formation has been coupled to the flue gas chemistry and fuel composition for short term exposures. The conclusion from the project is that probe exposures are a relevant for estimating the life time of superheaters.

Keywords: probe exposures, corrosion rate determination, corrosion in waste fired boilers, Correlation between fuel and deposit composition

Project KME-519 FeCrAl alloys as components in biomass- and waste fired boilers with sulphur additives

Project leader: Kristina Hellström, Chalmers

Characteristic for super heater corrosion in biomass and waste fired boilers is the combination of relatively low metal temperature and a chemically aggressive environment. The materials conventionally used in these severely corrosive applications are chromia-forming. However, certain chemical reactions, especially formation of alkali chromate (VI), that deplete the protective oxide in chromia tends to convert the oxide into poorly protective iron oxide and can result in a sudden increase in corrosion rate (breakaway corrosion). One possible strategy to avoid the problems would be to use a completely different type of materials that form protective oxide films not attacked by alkali at the temperature range of interest. One solution would be to use alumina-forming alloys such as the well-known FeCrAl steels in these environments. It also known that the corrosiveness of the environment is decreased when introducing sulphur-containing species in the boiler.

Hence, In this project the corrosion behavior of a alumina forming FeCrAl alloy, Kanthal® APMT, was investigated at 600 °C in 5 % O2 + 40 % H2O + 300 ppm SO2 with and without the presence of KCl. The influence of pre-oxidation was also examined. The exposures were performed in laboratory furnaces with a well-controlled atmosphere. The kinetics was followed using mass gain measurements. The formed corrosion product was examined by a range of analytical instruments (XRD, SED/EDX, AES, IC and SIMS) to evaluate the corrosion course of event.

The mass gain of Kanthal® APMT is very low both in the presence of SO2 and without SO2. The mass gain is 20 times lower compared to 304L after exposure in the presence of SO2. Initially a layered oxide forms with an inner alumina, a middle chromia and an outer Fe-rich oxide. The oxidation appears to proceed by inward diffusion of O2- to the oxide/metal interface a by outward diffusion of Al3+ to the oxide/gas interface. SO2 appears to inhibit the outward growth of the alumina scale. S enrichments are found on the surface and in the oxide scale, situated between the alumina scale and the Cr enrichment. Exposing the material in the presence of SO2 and KCl increases the oxidation rate considerably compared to an environment without KCl. More than half of the applied KCl is converted to stable K2SO4 on the material surface during exposure. Cl was present where corrosion had started implying alloy chlorination. Pre-oxidation decreases the corrosion rate even further. However some spallation has occurred, likely as a result of thermal expansion miss match and/or alloy chlorination. After spallation the alumina scale is likely not re-healed due to the low Al diffusion rate at the exposure temperature.

Hence, the alumina forming FeCrAl material Kanthal® APMT is not completely inert to KCl in an oxidizing SO2 containing atmosphere at 600°C. However, the corrosion rate is significantly lower than for the chromia forming 304L. Pre-oxidation decreases the corrosion rate even further, making Kanthal® APMT a promising candidate material for combustion plant components from a corrosion point of view.

Keywords: FeCrAl alloys, alumina, sulphur dioxide, potassium chloride

Project KME-521 Thermomechanical fatigue in virgin and aged stainless steels

Project leader: Johan Moverare, LiU

Thermomechanical fatigue testing has been performed on several different austenitic stainless steels. The materials considered in the project represents a mix of well established materials and new potentially better materials for power plants with biofuel or waste fractions as fuel. The project is a collaboration between the division of Engineering Materials at Linköping University and Sandvik Materials Technology. Due to the very late start of the project (March 2013) all of the initial project goals are not fulfilled yet and only limited results are available so far (When this report is written 3 of 6 different materials have been tested in the virgin condition). The most important findings so far are however summarized below:

- In-phase TMF with a maximum temperature of 800°C has been performed.
- A comparison between Sanicro 25 and AISI 310H show that the two alloys have essentially the same resistance to thermomechanical fatigue when subjected to mechanical strain ranges lower than 0.6% (fatigue lifes longer than 1000 cycles to failure). For higher strain ranges AISI 310H show and adventage due to higher cyclic ductility and longer fatigue life. However, Sanicro 25 clearly demonstrates an advantage in strength at both low and high temperatures.
- Exposure at 800°C promotes the formation of precipitates along grain boundaries in Sanicro 25. These precipitates contribute to the formation of voids and microcracking during tensile straining which leads to a reduction in ductility. Similar failure mechanisms are also seen after thermomechanical fatigue testing.

Keywords: Thermomechanical Fatigue, Austenitic Stainless Steels, Creep and Tensile properties, Effect of ageing

Project KME-601 More Effective Power Production from Renewable Fuels – Reference Power Plant (RPP)

Project leader: Erik Skog, Erik Skog AB

The KME program has a goal to demonstrate high electrical efficiency with renewable fuels in a full-scale plant. The project KME -601 has studied how plants could be built to meet the project goal of 3-4 %-unit efficiency increase of electricity production.

Plants with steam data up to 600 °C are currently in operation with fossil fuels. Renewable fuels contain species (K, Na) that can cause excessive corrosion of the superheater tubes. The introduction of carbon dioxide tax in Sweden on district heat production with fossil fuels in 1991, generated rebuilt and construction of new plants for renewable fuels. Severe damage on superheater tubes occurred and initiated research and development in the area. The trend towards higher steam data then stalled for the renewable fuels. Today sufficient knowledge to mitigate the corrosion and approach steam data as for fossil-fired plants is possible.

Two fuel mixes has been used in the project; Virgin (forest residues) and Wide (75 % recycled wood and 25% Virgin) and three different plant sizes; 100, 50 and 25 MW_e. The heat production has been kept constant when calculating the plant performance for varies steam data.

Different plant concepts including a base case with "normal" steam data were evaluated with process calculations in Thermoflex. A number of concepts where selected for design and cost calculations. Risks has been assessed and dealt with different design or system solutions. Operating costs have been calculated including changes that the selected steam data could cause.

For "Virgin" fuel up to 3.6 % increase in electric efficiency can be achieved with steam data of 175/46 bar and 600/600 °C in cogeneration. Profitability and constraints in partial load makes it less interesting. For condensing operation and larger plant sizes reheat is more interesting. A simple steam cycle with 175 bar and 600 °C, which achieves 2.3% and have acceptable operating characteristics is more likely for CHP application. Profitability is better than the base case for the larger plant, but lower for the smaller ones.

The "Wide" fuel plant achieves an increase of up to 3.8 % with steam data at 160/44 bar and 560/560 °C in both cogeneration and condensing operation. For a simple steam cycle at 160 bar and 560 °C, about 2.8 % is achieved. Profitability for the "Wide" fuel is better even for the smaller plant sizes.

The project goal to increase the electrical efficiency of 3-4% units can be achieved with renewable fuels. Profitability with current Swedish conditions is possible with pure forest fuels for plants of the 100 MW_e size. The efficiency increase is somewhat lower for Swedish conditions. For renewable fuels with 75% recycled wood it's profitable for the plant size from 25 MW_e and above. For installations with condensing operating profitability is very good. Proposal for development activities have been provided to the KME program and the generation of new projects.

The profitability for the advanced concepts with high efficiency is off course dependent on several factors, where the development of total electricity prices, including green certificates or feed-in tariffs, and fuel prices are of special importance. The mentioned profitability is valid for presented conditions in Sweden, comprising factors that will vary in time and for different markets. This “green” investment will give an significant increase in the production of renewable electricity, based on a limited heat sink for the CHP case, or based on a limited biomass fuel volume for the condensing case. How this will be evaluated and which profitability requirements that will be valid can vary between different stakeholders.

Keywords: Cogeneration, Renewable fuels, high electrical efficiency, 600 °C steam temperature

Project KME 607 Improved steam turbine design for optimum efficiency and reduced cost of ownership

Project leader: Magnus Genrup, LU

The cost of ownership of a power plant is partly governed by the efficiency of the turbine island. The turbine stands for the production revenues when transferring the fuel into electric power and district heating. One gauge of the quality of the individual processes is the component efficiency – the current project addresses the turbine part of the power plant. The turbine efficiency is dependent on both process parameters and the blading aerodynamics. The former is typically the steam data (e.g. temperature, pressure and mass flow) that influences the volumetric flow through the turbine. A larger turbine performs better than a smaller ditto and this can be explained by the relative importance of clearance- and secondary flows. The blading aerodynamics is the local flow processes in each stage in the turbine. The efficiency of a stage (i.e. a stator and a rotor) is limited by losses due to e.g. dissipation in boundary layers, dissipating of secondary flows, leakage mixing and lost work, etc. The project has been conducted in collaboration between the department of Energy Sciences at Lund University and Siemens Industrial Turbomachinery in Finspong.

Most previous development efforts in the industrial steam turbine segment has been towards reduced first cost and not necessarily the efficiency. Most industrial steam turbines utilizes prismatic (or un-twisted) blades for shorter stages. The word “shorter” is used in a sense that all stages except for the last three are constant section blades. The last stages have to be designed for large span-wise flow variations by three-dimensional blade shapes. A constant section rotor blade typically is milled in a two-axis machine whilst more advanced shapes requires five-axis flank milling. The costs associated with the latter has today levelled with the more simple manufacturing methods. This technology step has been introduced in larger size utility type of turbines with very high attainable efficiency levels. An industrial size steam turbine cannot reach the same level of efficiency and lags several points behind as for a utility type unit, because of the lower volumetric flow and the cylinder pressure ratio.

The goal of the project can be summarized as “exploring the future flow path for higher-performing steam turbine plants” by evaluating the maximum cost effective efficiency potential of industrial steam turbines. The latter is by utilizing improved blade profiles and advance stacking technologies.

The work has been carried out in state-of-the-art turbine design tools and comprises: one-dimensional tool, two-dimensional throughflow analysis and full three-dimensional high-fidelity CFD. The latter was not part of the initial plan but was introduced because it was necessary to establish a baseline for back-to-back comparisons. The datum stage is a tall stage in an assumed Siemens SST-900 turbine. The work, however, is generic for low-reaction steam turbines.

The work shows that the stage performance can be increased. The full potential, however, is still to be evaluated as the work continuous in the project. The project work at Lund University effectively started in late 2012 and is not yet completed.

Keywords: Steam Turbine, Aerodynamics, Flow Path Design, Efficiency

Project KME-608 Study of corrosion memory in boiler heat surfaces by field tests with biomass fuel mixes including sulphur and refuse fractions

Project leader: Lars Wrangensten and Tom Sandberg, Pöyry

An increased knowledge of the relationship between dynamic corrosion mechanisms, fuel specification and possible steam operation temperatures can form a platform for how to implement gliding steam temperature control. There is a vast economic potential to optimize and correlate the boiler operation to current fuel quality and continuously use the increased net income potential within an advanced boiler. This phenomenon can be referred to as the corrosion attack during operation due to historic boiler operation (which have resulted in certain deposits and corrosion products) rather than the fuel mix currently being used (corrosion memory). Thus, the formations of oxide scales and thick deposits from the past dictate the corrosion further on. As a consequence, the corrosion memory effect can be divided into two sub-areas; namely increased corrosion due to irreversible depletion of the steel and secondly the rate of conversion of corrosive deposits. A boiler using the gliding temperature concept is more susceptible for this type of accelerated corrosion compared to conventional boilers. This since the change of steam temperature needs to be chosen, not only with respect to the corrosiveness of the current fuel mix, but also with respect to former corrosion history.

The present project is a first step to increase the knowledge of materials technology process solutions to minimize superheater corrosion with advanced steam data in boilers. The project consists of two major exposure campaigns, namely the “pre-study” and the “main study”. The main aim of the pre-study was to investigate the kinetics of reactions related to deposit build-up and conversion versus material temperature. Thus, increasing the knowledge in one of the two corrosion memory two sub-areas described above; namely the rate of conversion of corrosive deposits. The pre-study showed that increasing the exposure time and the temperature implies that the conversion of KCl to K_2SO_4 is also increased. A non-corrosive deposit (represented by pure K_2SO_4) may form a protective barrier between a corrosive deposit and the alloy when exposed in a corrosive fuel such as in a waste fired boiler (P14 in Norrköping). However, all non-corrosive deposits had a tendency to spall off, i.e. both the artificial deposit K_2SO_4 and the one formed in the co-fired boiler P13 in Norrköping, co-firing forest residue, tyre derived fuel and recycled wood waste. The main study showed that the corrosion rate was lower for the sample exposed in P13-P14-P13 compared to the sample exposed in P14 despite longer exposure time showing a positive “memory effect” of the deposit formed in P13. One of the challenges in the project was that all non-corrosive deposits had a tendency to spall off, i.e. both the artificial deposit K_2SO_4 and the one formed in the P13 boiler, which influences the results. This should be taken into account in future projects, as this is an initial investigation regarding the corrosion memory effect. These studies of both the kinetics of artificial deposits in a real boiler as well as actual corrosion probe test in two commercial boilers new knowledge about the corrosion memory effect have been obtained.

Keywords: Waste combustion, Biomass combustion, Corrosion memory, Probes

Project KME-609 Technical and economical risks for plant concepts with advanced steam data for biomass-fired CHP demonstration plant

Project leader: Raziyeh Khodayari, Vattefall

In KME-601, generic plant concepts that will form the basis of the demonstration plant have been developed. Results from KME-601 indicate that a detailed study of the technical and economic risks of the developed generic plant concepts is required as a part of the decision basis for the potential demonstration plant. The goal of KME-609 is thus to make a more thorough evaluation of the technical and economic risks. Included objectives are:

1. Define non-conventional parts that needs to be demonstrated, identify technical risks for these parts and quantify the risks in monetary terms
2. To evaluate economical/project risks for the plant e.g. procurement, guarantees and risk sharing
3. To evaluate a "fall-back" option to be used for reducing the risk if there are operational problems at the advanced steam data level.
4. To investigate how to finance the additional risk for a demonstration plant

From KME-601 the following two plant concepts are selected

1. For virgin biomass fuels, 100 MWe
    1. Advanced steam data 175 bar/600^{o}C
    2. Conventional steam data 140 bar/540^{o}C
2. For wide fuel mix, 50MWe
    1. Advanced steam data 160 bar/563^{o}C
    2. Conventional steam data 90 bar/500^{o}C

For the virgin fuel, the major risks are creep and fatigue of final superheater, availability of turbine, steam side oxidation, and carry over from steam side oxidation on the superheater and steam turbine. The underlying design parameter for these risks is the increased steam temperature of 600^{o}C introducing material both for the final super heater and turbine not available in the market today.

For wide fuel mix, the major risks are, corrosion and increased metal loss on furnace walls, not gas tight or cracked SiC refractory, metal loss (corrosion) higher than expected in evaporator and superheater, and lower/higher flue gas temperature out of the furnace. The most important parameter for the wide fuel case is the increased steam pressure, resulting in an elevated temperature in the furnace walls, thus increasing the risk for mid-temperature corrosion.

When the risk is translated into monetary terms and included as an annual cost for studied concepts it is shown that the economic feasibility is lower for the advanced steam data compared to the reference steam data. The increased efficiency of the advanced steam data is thus not enough to cover the increased risk cost. Comparing the different fuel cases also shows that the risk cost is higher for the wide fuel case resulting in a larger decrease in NPV. However the NPV for the advanced steam data without including risks is higher for the wide. The extra risk in the wide fuel case is therefore motivated by a possible increased profitability.

The relative size of the required extra capital funding, to eliminate the negative impact from the most probable risk value, is between 17 % and 32 % of the additional plant investment needed when going from conventional to advanced steam data. The level of these capital funding are in the same range as the funding possibilities identified in this report. The most important are Horizon 2020 and the Swedish energy agency (SEA).

For both fuel cases fall-back options have been defined with the prerequisites to identify a fail-safe mode with the highest economic feasibility. For the virgin fuel case, the fall-back option means reduced steam temperature from 600 to 570°C. The economic analysis shows that this fall-back option is potentially feasible compared to the NPV with the reference steam data.

A definition of a safe and economic feasible fall-back option for the wide fuel case is more difficult, since also the pressure is very elevated in the advanced concepts compared to reference case. Therefore both the steam parameters and the share of waste wood are considered as possible parameters to vary. However an economic feasible fall-back option has not been identified for the wide fuel case and the largest negative impact for this fuel case occurs when the share of waste wood is reduced down to 15% (energy based). The relatively best option is to maintain the fuel mix and reduce the steam data down to 90 bar/520°C. For the wide fuel case it is suggested to further optimise the fall-back option, the goal for this optimisation would be to increase the steam data without reducing the share of waste wood in the fuel mix. When comparing the risk cost with the fall-back option, it is clear that the fall-back option in the virgin fuel case has the same or better NPV. For the wide fuel case the opposite relation exists. Again this stresses that the fall-back option for the wide fuel case needs to be further developed

The concept must also be commercially attractive enough for a buyer and supplier to be willing to take the risk of engaging in a Demo-project. Besides the technical risks some economical/project risks have therefore been addressed.

- Certain plant sections will not be covered by normal commercial guarantees, it is recommended that these parts are handled by risk sharing between supplier and buyer. One suggested measure is to set up a monitoring program linked with a risk sharing/bonus system. Probably the most important measure to handle the risks and guarantee issues in the project, is however to perform up-front testing of the advanced design measures.
- Multiple contract for procurement and inquiring advanced steam data as optional is suggested, both as a mean to reduce the risk for the suppliers and a mean to increase the possible number of bidders.

Keyword: renewable solid biofuels, advanced steam data, high electrical efficiency, 600°C

Project KME-52 Synthesis of the KME Research Programme

Project leader: Ronny Nilsson

KME is a research programme with material technology development as a base to enhance efficiency in thermal energy conversion processes using climate neutral fuels and waste fuels, as well as to increase availability and reduce maintenance costs. The programme was established in 1997 and its fifth phase, 2010–2013, has recently been completed. The programme has as its vision to contribute to transformation of the energy system in Sweden and the EU into a society which is sustainable in the long term by using materials technology development as a basis as well as ensuring Swedish industry is internationally competitive. The vision is intended to be reached via development of more efficient and flexible thermal energy conversion processes using renewable and waste fuels and enable power production with electrical efficiency 3-4 percentage units higher than presently available technologies. On top of efficiency, flexibility and environmental performance the demand for materials capable of more cyclic operation has been increased substantially due to introduction of high levels of volatile wind and solar power capacity. The main problem areas in energy conversion with renewable and waste fuels are high temperature corrosion in superheaters, furnace waterwall corrosion and low temperature corrosion in economizers and air preheater sections, derived from fouling of corrosive compounds, such as solid or molten metal chlorides. These problems finally lead to reduced availability and increased maintenance and repair costs.

The results of the research efforts in KME during previous programme stages have contributed to higher superheater temperatures for CFB boilers after introducing the final superheater in the loop seal with significantly reduced risk for high temperature corrosion, while also making it possible to increase final superheater temperature. Other key progress made possible by KME research efforts for mitigating high temperature corrosion and increasing steam temperature and/or increasing life time of superheaters is to inject sulphur based additives into the combustion process. KME has contributed in developing a new design for the final superheater when firing waste fuels and RDF. By introducing double tubing the tube surface temperature can be increased above the critical “window” for high temperature corrosion.

The main results from recent KME stages with respect to research on **materials for boilers for biomass and waste fired plants at elevated temperatures** concerns alumina-forming steels, additives and improved methods for estimation of lifetime for boiler components.

As low alloy steels are unsuitable for use as superheater or furnace wall materials in biomass and waste fired plants at medium to high steam data more corrosion resistant materials are needed. The most corrosion resistant materials that are currently widely used in waste fired boilers are highly alloyed stainless steels or nickel base alloys. These have excellent corrosion resistance, but are expensive. In the KME programme it was shown that alumina-forming (FeCrAl) steels also had good performance. These alloys contain less alloying elements and are expected to be cheaper. However, they become embrittled at the service temperature, but they could be used as coatings. FeCrAl steels with lower chromium contents did not become brittle and will be investigated further.

Additives have been found to be an effective way of reducing corrosion. Kaolin and digested sewage sludge were the most promising additives for reducing corrosion in the furnace region of a boiler burning waste wood. They were also the most promising for reducing furnace wall and superheater corrosion at the same time. However as sewage sludge has a negative cost (plants are paid for burning it) this is the additive to be preferred on an economic basis. Sulphur-based additives were effective in reducing superheater corrosion only. All these additives are a means of increasing fuel flexibility.

It was also found that long-term probe testing (6 weeks or more) could be used to estimate the life of components like furnace walls and superheaters.

With regard to research on **materials for gas turbines** the main results from recent year's research are substantial progress with respect to development of superalloys for gas turbines and design criteria for thermo-mechanical fatigue (TMF) which has given useful input to development of a new single crystal material aimed to better fulfil requirements regarding fuel flexibility and cyclic operation in future gas turbines. As one consequence of the research, Siemens has, as one of few turbine manufacturers, replaced conventional design data with TMF data for temperatures above 600°C.

Thermal Barrier Coatings (TBC) are widely used for protection against oxidation and corrosion at elevated temperatures. Research has been performed on metallic coatings, which have superior temperature properties than TBC, but tolerate almost no loads. The metallic coatings can be used alone or as part of TBC. Promising metallic coatings have been identified and two new coatings have been patented during the latest stage of KME.

The KME results of materials research are proven to contribute to improvement of components and processes for both existing and new plants, boilers as well as steam and gas turbines.

With regard to **process and plant development** it was during the latest stages of KME a major goal to study and evaluate advanced and high efficiency concepts for CHP plants, "Reference Power Plants (RPP)", for biomass fuels that could be demonstrated in a full scale plant. The work has been done in co-operation between manufacturers and energy utilities.

The focus has been to increase steam data in biomass and waste fired power and CHP plants, considering design with regards to heat balance and corrosion as well as impact on investment, O&M costs and availability.

Design studies for biomass fuels (forestry residue, wood chips, bark, etc) show an efficiency improvement of +2.3%, with an increase of steam data to 175 bar, 600°C, and +3.1% for a reheat option (175/46 bar, 585/585°C) compared to conventional plants (140 bar, 540°C). These would be feasible for capacities 50-100 MWe. Further full load improvement is of course possible by increasing temperature 600/600°C, which could be of interest for condensing plants.

The number of challenges increases for the wide fuel range, for the studied case defined as 75% waste wood and 25% biomass. In addition to high temperature corrosion risk, among other risks, mid temperature corrosion (mainly furnace corrosion) and cold end corrosion, have to be considered in the boiler design.

Selected concepts (160 bar 560°C and 160/44 bar 560/560 °C) cases have been regarded as technically feasible, but calls for significant measures, in terms of design and mitigation of corrosion risks. The efficiency improvement for main advanced steam data options compared to benchmark is in the range of 2.8-3.8 %.

In addition to the design studies risks that can be present for the first full-scale demonstration plant with advanced steam data have been studied, identifying major risks and challenges in the demonstration phase. Fall-back options have been defined with the prerequisites to identify a fail-safe mode with the uppermost economic feasibility.

KME offers opportunities for a forum where material producers, system and component manufacturers and end users meet to discuss and consider problems and possible solutions together with experienced and competent researchers. KME assists in this sense in creating a unified understanding of problem scenarios and increases the possibility of new solutions.

The coming KME programme stage 2014-2018 is designed to continue materials research for more fundamental knowledge of materials to be applied and demonstrated in new advanced processes and applications for energy conversion and to demonstrate and implement more effective thermal processes for electricity and heat production in both existing and new plants.

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