### *Project*

# Influence of high-temperature environments on the mechanical behaviours of high-temperature austenitic stainless steels

# Temperaturpåverkan på egenskaperna hos högtemperaturtåliga austenitiska rostfria stål

This project proposal is a continuation of KME 501 and KME 521.

### *Applying organisation*

Linköping University, Department of Management and Engineering, Division of Engineering Materials

### *Organisation number:*

202100-3096

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## Sammanfattning

Dagens och morgondagens krav på elproducenter att producera el utifrån givna förutsättningar innebärande införandet av nya och icke fossila energi slag. Nya krav på ökat korrosionsmotstånd, högre tryck och temperatur samt förmåga att tåla cyklisk drift har inneburit att krav på nya mer högpresterande material uppkommit. Dessutom har de förändrade driftförhållandena medfört krav på alternativa provningsmetoder och därmed karaktärisering av mikrostruktur. Detta projekt kommer att undersöka befintliga och nya material för komponenter som används i de mest påkända delarna i anläggningar för energiproduktion där ickefossila bränslen utgör en viktig del och där effektivisering är ett viktigt krav. I undersökningarna kommer tidigare framtagna metoder anpassade till cykliska driftförhållanden och omfattande mikrostrukturstudier med syfte att klarlägga skade- och livslängdsmekanismer. Resultaten av undersökningarna kommer att innebära att konstruktörer kommer att kunna göra bättre materialval i framtidens anläggningar och utföra säkrare livslängdsanalyser.

## Summary

Energy production for tomorrows needs means introduction of new energy sources and non-fossil production. More recent and narrower specifications concerning corrosion, cyclic use, higher temperature and pressure has put demands on development of new and more resistant materials. This in turn has created a need for new testing methods and characterisation techniques of microstructure to take care of deformation and damage mechanisms and life modelling. In this project todays materials and newly developed materials for high performance components in the hotter part of non-fossil fuel power plants will be investigated. In the project methods for testing using non static loading to evaluate cyclic user conditions, produced in a previous project will be applied like low strain rate testing and thermomechanical testing together with extensive studies of microstructure in order to clarify damage and life determinant mechanisms. The results produced will allow designers to perform improved materials selection and to do more accurate life prediction.

## Motivation

One of the main objectives for KME during the program period 2014-2017 is improved operation flexibility, and the option of cyclic operation of thermal energy processes. Investigation of opportunities and obstacles for greater steam data corresponding to the long-term ambition of increasing power plant efficiency which means at minimum an increase of 40 °C to 50 °C in steam temperature for biomass power plant is another goal for this program period. To avoid cracking or failure due to the increased steam data and cyclic operation conditions, studies are necessary to establish the most detrimental mechanism for the mechanical service life of the materials in relation to the new demands. However, the temperature limit for long-term application of the present ferritic steels in steam power plants has been reached and new material groups needs to be explored for this purpose. The need for more corrosion resistant material also increases with the introduction of biofuel and renewable waste fractions and for this purpose austenitic materials can be an attractive alternative. In general austenitic materials have a higher coefficient of thermal expansion and lower thermal conductivity compared to ferritic steels. As a consequence, higher thermal stresses will develop in austentic materials compared to ferritic steels for a given thermal cycle. This means that better knowledge of the thermomechanical fatigue behaviour of stainless steels are needed in order to verify that these materials are a long-term solution for power plants with increased steam temperatures and more corrosive environments. The results from this project can be used for improving the design of new and more advanced boilers for biofuel. Better knowledge of thermal fatigue and degradation mechanisms as e.g. stress relaxation cracking, will lead to increased safety and longer component life times. The results will also be an important basis for proper material selection of more corrosion resistant alloys.

### *Contribution to KME´s goals*

Especially this project addresses the following goals of the KME-program: “To evaluate the mechanical properties and service life of various materials in relation to new material requirements for more efficient electricity production (elevated pressures and temperatures)” and “To develop methods for quantifying processability for new materials, as well as creating an understanding of microstructure development and mechanical properties for more efficient energy plants”. From a material perspective this project will also examine the most detrimental obstacles related to the goal of “examine opportunities and obstacles with regard to how plants can achieve greater steam data corresponding to the long-term ambition of electrical efficiency which is 3-4 percentage units higher than the best technology for a given fuel at present”. The proposed project will also contribute with material a design tool for implementation of new material in these power plants corresponding to the KME goal “To further develop tools and techniques to facilitate the application of new material solutions in plants”.

### *Energy relevance*

This project will contribute with investigations of candidate materials with improved oxidation and corrosion resistance than the materials that are used today, which is needed for improved fuel flexibility. It also investigates these materials in testing that is more similar to the cyclic operation conditions that the new generation biomass power plant will require. The proposed project will give useful tool for further material development for future high-temperature environment applications as biomass power plants.

### *Industrial relevance*

Sandvik Materials Technology and Sandvik Heating Technology are companies providing high temperature resistance materials. The material properties such as creep and low cycle fatigue interaction, stress relaxation cracking, structure stability and thermomechanical fatigue are important to material development and also applications.

### *General applicability*

This project is directly related to the concern of safety and reliability to the material manufacturer and end user, which provides understanding, and safety and reliability guidance to the material. The results can be used for boiler design, safety consideration, material design and improvement, and consequently competitive ability.

### *New values with the project*

New efficient methods to evaluate the degradation mechanism stress relaxation cracking and a new method to determine creep properties using very slow strain rate tensile testing are expected to be achieved. Characterisation of a newly developed advanced heat resistant material (Sandvik Sanicro™ 25) will be done.

### *Implementation of results*

The results can be directly used for:

a) Safety and reliability analysis for the power plant resulting in higher efficiency.
b) Material selection for design of the power plant with higher efficiency and flexibility.
c) Development of new materials

## Background – State of the art

Biomass is the largest global contributor to renewable energy and has a great potential to expand in the production of heat and electricity [1]. It is a sustainable fuel because it gives no net contribution of $CO_2$ to the atmosphere and it can be considered endless [1,2]. However, the global increase in energy consumption and the increase in emissions of greenhouse gases (e.g. $CO_2$) causing global warming, make needs for both an increase in energy production and a reduction of greenhouse gas emission [3,4]. One way to accomplish both needs is to increase the efficiency of biomass power plants, which could be reached by increasing temperature and pressure in the boiler sections [5]. Thus, the requirement of more energy production is met and since biomass has no net contribution of $CO_2$ to the atmosphere less emissions of greenhouse gases is the result.
The materials used for future biomass power plants with higher efficiency are required to display improved properties such as higher yield strength, creep strength and high-temperature corrosion resistance. The performance of austenitic stainless steels at these elevated temperatures is not yet fully understood [6,7].
For instance the degradation mechanism acting on austenitic alloys at elevated temperatures called stress relaxation cracking (SRC) is not fully understood. It may result in failures in components after short time of operation in spite of the use of approved materials [8,9]. Standardised tests at ambient- or high temperatures like creep-, tensile-, fracture toughness- or fatigue tests have not been successful in predicting the failures. Examples of SRC have been reported in chemical process industry for example by van Wortel [8], and the alloys treated are also used in boilers. Common denominators for the failures experienced in applications are the presence of residual stresses from either cold forming like for example bending, or from welding. The operating metal temperature is generally between 550°C and 750°C, and the alloys used have shown a poor ductility also recognised in low creep ductility at these temperatures [8,9]. It is reported that SRC can be avoided by post-weld and post-bend heat treatments [10], however these actions may be costly and sometimes even impossible to perform for geometrical reasons. There is a need for an efficient method to evaluate SRC to increase the knowledge about SRC and also supporting material design to prevent SRC. A first step to achieve such method has been taken in the

preceding KME 501 project. However, more work has to be done to reach a useful and efficient method [11].

Since the life time of power plant is expected to be 30 years or more [12], materials with better long term high-temperature performances, as safety and structural integrity [13], are desirable. More knowledge is needed in order to verify that austenitic stainless steels are a long term solution for power plants with increased steam temperatures and more corrosive environments. Biomass power plants are supposed to withstand many start and stop cycles to maintain efficiency in the global energy and electricity network. This advocates for investigations of how cyclic operation conditions influence the high-temperature performance of austenitic stainless steels.

One way to investigate the cyclic high-temperature properties of the materials used in new more efficient biomass power plants is to study the thermomechanical fatigue (TMF) behaviour [14]. It is very likely that an SRC-type of failure mechanism will be active during TMF provided that the dwell time in the IP-TMF tests is sufficiently long. However, this is a topic where very little research has been conducted [15].

Other suggested methods to evaluate high-temperature behaviour of advanced heat resistant materials is very slow strain rate testing (SSRT) which can lead to similar analysis as creep tests at high stresses [16]. The advantage of SSRT compared to regular creep testing is that SSRT are much faster, and in the early stage of material development this could be a large benefit if the method gives reliable and appropriate data. Especially if modelling and estimation of life could be based on SSRT data instead of or as a complement to data creep tests. In KME 501 damage and fracture mechanisms have been identified for a range of alloys and conditions, as varied strain rates and temperatures [11,17,18,19,20] and data for modelling have been established [11].

The proposed project is a continuation of KME 501 [11] and KME 521 [15] and the results from this project can be used for improving the design of new and more advanced components used in energy conversion systems based on biofuel. Better knowledge of thermal fatigue and degradation will lead to increased safety and longer component life times. The results will also be an important basis for proper material design and selection of alloys for high-temperature environments.

## References

[1] Sadrul Islam, AKM, Ahiduzzaman, M. AIP Conference Proceedings 2012;1440:23.

[2] Pettersson, J, Asteman, H, Svensson, J, Johansson, L. Oxidation of Metals 2005;64:23.

[3] Margolin BZ, Shvetsova VA, Karzov GP. Int.J.Pressure Vessels Piping 1997;72:73.

[4] Trygg L, Amiri S. Appl.Energy 2007;84:1319.

[5] YIN J, WU Z. Chin.J.Chem.Eng. 2009;17:849.

[6] Viklund P, Hjörnhede A, Henderson P, Stålenheim A, Pettersson R. Fuel Process Technol 2013;105:106.

[7] Reed RC. Superalloys: fundamentals and applications. Cambridge: Cambridge University Press, 2006.

[8] Van Wortel, H. NACE - International Corrosion Conference Series 2007:074231.

[9] Benac D, Olson D, Urzendowski M. Journal of Failure Analysis and Prevention 2011;11:251.

[10] Panchal VD. World Pumps 2013;2013:28.

[11] Johansson S. Final report (2014); KME 501.

[12] Sourmail T. Materials Science and Technology 2001;17:1.

[13] Calmunger M, Chai G, Johansson S, Moverare J. ICF13 2013

[14] Christ H-. Materials Science and Engineering A 2007;468-470:98.

[15] Moverare J. Final report (2014); KME 521.

[16] Oh H. J.Mater.Process.Technol. 1996;59:294.

[17] Calmunger M, Chai G, Johansson S, Moverare J. ICF13 2013

[18] Calmunger M, Chai G, Johansson S, Moverare J. ECF19 2012

[19] Calmunger M, Chai G, Johansson S, Moverare J. Key Engineering Materials 2014;592-593:590.

[20] Calmunger M, Peng RL, Chai G, Johansson S, Moverare J. Key Engineering Materials 2014;592-593:497.

## Goal

Increase of the efficiency of a biomass power plant is obtained mainly by increasing temperature and pressure. The materials used will suffer from a tougher environment resulting in safety and reliability problems. The main purposes of this project are to evaluate the mechanical behaviours for structure safety and integrity analysis, namely:

a) To evaluate the creep and LCF interaction diagram of the boiler materials for material selection and integrity analysis since the boiler materials can undertake both creep and low cycle fatigue during the service.
b) To evaluate the structure stability and the toughness of the materials after long term service at a temperature higher than 650°C and service time longer than 20000 hours for safety analysis.
c) To evaluate thermo-mechanical fatigue properties of the boiler materials for safety and life evaluation since the power plants can start/shutdown quite often during service for energy saving and flexibility purposes in the future.
d) To evaluate the stress relaxation cracking behaviour of the boiler material. It is critical problem for some boiler materials.

## Project plan

The project plan consists of the following four parts including testing and material characterisation:

### Materials

The materials of interest are AISI 310M, AISI 347H, Sanicro 25, Alloy 800HT and Alloy 617. The materials represent a mix of well-established materials for this type of application and new potentially better materials.

### Part 1: Creep and low cycle fatigue interaction and very slow strain rate testing and creep

Creep and LCF interaction behaviour will be studied, and creep and LCF interaction diagram will be built according to ASTM standard E262.
Very slow strain rate testing (VSSRT) will be performed in an electromechanical tensile test machine evaluating creep properties and comparing with regular creep test in similar condition.

#### *Task 1-1: Creep and LCF interaction behaviour*

Creep and low cycle fatigue testing will be performed to study the damage behaviour due to the interaction between creep and low cycle fatigue. The diagram of creep and low cycle fatigue interaction will be built.

#### *Task 1-2: Creep testing*

Creep tests and VSSRT using a strain rate of $10^{-7}$/s will be performed at elevated temperatures.

## Part 2: Long-term ageing

Long-term ageing will continue from KME 501. By performing long-term ageing at 650 °C and 700 °C for 20 000 and 30 000 hours the effect of service degradation will be taken into account. At the chosen temperatures these types of materials are in general very prone to precipitates of secondary phases leading to a significant degradation of the materials structural integrity.

### *Task 2-1: Influence of long-term ageing on toughness*

Impact and fracture toughness test will be performed after 20 000 hours and 30 000 hours ageing process, using Charpy V and CTOD methods respectively.

### *Task 2-2: Structure integrity evaluation*

Using failure assessment diagram and the long-term ageing results from task 2-1 and KME 501, the influence of long-term exposure in high-temperature environments on structural integrity of the heat resistant materials will be evaluated.

## Part 3: Thermomechanical fatigue testing

Thermomechanical fatigue testing will be performed on long-term aged austenitic alloys.

### *Task 3-1: Long-term ageing before TMF testing*

Long-term ageing will be performed on virgin and pre-strained material. By performing long-term ageing at 800 °C for 2000 hours the effect of service degradation will be taken into account.

### *Task 3-2: Thermomechanical fatigue testing*

The resistance to TMF failure for both an IP and an OP TMF cycle will be analysed and compared for all materials. The maximum temperature in the tests will be 800 °C which is rather high for this type of application. However, for practical reasons the tests need to be accelerated with respect to time and the hold time applied at the maximum temperature is only 5 min in each load cycle. In order to somewhat compensate for these short exposure times during testing the maximum temperature is increased. Light optical microscopy (LOM), transmission electron microscopy (TEM) and scanning electron microscopy (SEM) techniques as electron channelling contrast imaging (ECCI) and electron backscatter diffraction (EBSD) will be used to analyse the deformation and damage mechanisms.

## Part 4: Stress relaxation cracking

Development of efficient methods for stress relaxation cracking (SRC) and tests will be performed on austenitic stainless steels and nickel-based alloys for characterisation and remedy to prevent it in future material design.

### *Task 4-1: Method development*

Two efficient methods will be developed, a screening method and a mechanism evaluation method. The screening method will be conducted to cold deformed and/or welded materials. The test will consist of bending to different degrees of deformation and then subjected to heat under constant strain. The mechanism evaluation method will use potential drop (PD) and an electromechanical tensile test machine to monitor both crack propagation and load. A small compact tension (CT) specimen with notch and pre-crack with a predefined plastic zone will be used. Microscopy as LOM and SEM will be used to analyse and verify the methods and SRC.

### *Task 4-2: Stress relaxation cracking behaviour of heat resistant materials*

In this task the alloys will be in as-received, cold deformed, aged and welded conditions. The methods will be conducted to the alloys for characterisation. For both methods LOM, transmission electron microscopy (TEM) and SEM techniques as ECCI and EBSD will be used to analyse if SRC is present in the microstructure and how it influence the microstructure.

### *Distribution of work*

| | Task 1 | Task 2 | Task 3 | Task 4 |
|---|---|---|---|---|
| LiU | VSSRT test, evaluation | Microstructure and evaluation | TMS testing and evaluation | CT testing and evaluation |
| Sandvik | Materials, LCF/creep test, evaluation | Materials, ageing, CTOD and impact testing | Materials and heat treatment | Materials Bending test and evaluation |

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## Time schedule

| Project tasks | 2014 | 2015 | | 2016 | | 2017 | | 2018 |
|---|---|---|---|---|---|---|---|---|
| Task 1-1 | | | | | | | | |
| Task 1-2 | | | | | | | | |
| Task 2-1 | | | | | | | | |
| Task 2-2 | | | | | | | | |
| Task 3-1 | | | | | | | | |
| Task 3-2 | | | | | | | | |
| Task 4-1 | | | | | | | | |
| Task 4-2 | | | | | | | | |
| Deliverables | | | | | D1 | | | |

D1: Ph.D. Thesis

## Industrial reference and financing

Industrial partner of the project will be Sandvik Materials Technology (SMT), SE-811 81 Sandviken and Sandvik Heating Technology (SHT), SE-734 27 Hallstahammar. The sum allocated at Sandvik Materials Technology to the project (as in kind contribution) is 3968000 SEK over 4 years. The sum allocated at Sandvik Heating Technology to the project (as in kind contribution) is 340000 SEK over 4 years.

### SMT

| **Kostnader** | **2014-09** | **2015** | **2016** | **2017** | **2018-04** | **Summa** |
|---|---|---|---|---|---|---|
| Lönekostnader | 150000 | 300000 | 300000 | 300000 | 100000 | 1150000 |
| Köpta tjänster | 0 | 0 | 0 | 0 | 0 | 0 |
| Utrustning | 0 | 0 | 0 | 0 | 0 | 0 |
| Material | 100000 | 234250 | 234250 | 234250 | 65000 | 867750 |
| Laboratoriekostnad | 318500 | 447750 | 447750 | 447750 | 238500 | 1900250 |
| Resor | 10000 | 10000 | 10000 | 10000 | 10000 | 50000 |
| Övriga kostnader | 0 | 0 | 0 | 0 | 0 | 0 |
| Indirekta kostnader | 0 | 0 | 0 | 0 | 0 | 0 |
| **Summa sökta medel** | **578500** | **992000** | **992000** | **992000** | **413500** | **3968000** |

### SHT

| **Kostnader** | **2014-09** | **2015** | **2016** | **2017** | **2018-04** | **Summa** |
|---|---|---|---|---|---|---|
| Lönekostnader | 20300 | 35000 | 35000 | 35000 | 14700 | 140000 |
| Köpta tjänster | 0 | 0 | 0 | 0 | 0 | 0 |
| Utrustning | 0 | 0 | 0 | 0 | 0 | 0 |
| Material | 30000 | 50000 | 50000 | 50000 | 20000 | 200000 |
| Laboratoriekostnad | 0 | 0 | 0 | 0 | 0 | 0 |
| Resor | 0 | 0 | 0 | 0 | 0 | 0 |
| Övriga kostnader | 0 | 0 | 0 | 0 | 0 | 0 |
| Indirekta kostnader | 0 | 0 | 0 | 0 | 0 | 0 |
| **Summa sökta medel** | **50300** | **85000** | **85000** | **85000** | **34700** | **340000** |

## Costs

| **Kostnader** | **2014-09** | **2015** | **2016** | **2017** | **2018-04** | **Summa** |
|---|---|---|---|---|---|---|
| Lönekostnader | 228300 | 492700 | 470600 | 480000 | 147400 | 1819000 |
| Köpta tjänster | 0 | 0 | 0 | 0 | 0 | 0 |
| Utrustning | 0 | 0 | 0 | 0 | 0 | 0 |
| Material | 5000 | 5500 | 5500 | 5500 | 5000 | 26500 |
| Laboratoriekostnad | 30000 | 35000 | 43000 | 43000 | 47000 | 198000 |
| Resor | 10000 | 10000 | 30000 | 20000 | 30000 | 100000 |
| Övriga kostnader | 0 | 0 | 0 | 0 | 0 | 0 |
| Indirekta kostnader | 145900 | 174800 | 168900 | 169500 | 69400 | 728500 |
| **Summa sökta medel** | **419200** | **718000** | **718000** | **718000** | **298800** | **2872000** |