KME

CONSORTIUM MATERIALS TECHNOLOGY for demonstration and development of thermal energy processes

Thermomechanical fatigue in virgin and aged stainless steels

UPDATED 2014-04-24

Johan Moverare, Jan Högberg, Guocai Chai
Raveendra Siriki

KME-521

Thermomechanical fatigue in virgin and aged stainless steels

UPDATED 2014-04-24

Johan Moverare, Jan Högberg, Guocai Chai
Raveendra Siriki

KME-521

Preface

The project has been performed within the framework 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 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 strengthen 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.

Abstract

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. Similar failure mechanisms are also seen after thermomechanical fatigue testing.

Sammanfattning

Termomekanisk utmattning (TMF) har utförts på flera olika austenitiska rostfria stål. De material som har inkluderats i studien representerar en blandning av väletablerade material och nya potentiellt bättre material avsedda för kraftverk med biobränsle eller avfall som huvudsakligt bränsle. Projektet är ett samarbete mellan avdelningen för Konstruktionsmaterial vid Linköpings Universitet och Sandvik Materials Technology. På grund av den sena projektstarten (mars 2013) har de ursprungliga projektmålen ännu inte uppfyllts och endast en begränsad mängd resultat är hittills tillgängliga (4 av total 6 material i jungfruligt tillstånd har testats vid sammanställningen av denna rapport). De viktigaste resultaten så här långt sammanfattas dock nedan:

- I-fas TMF-provning har genomförts med en maxtemperatur på 800°C.
- En jämförelse mellan Sanicro 25 och AISI 310H visar att de två legeringarna har i princip samma motstånd mot termomekanisk utmattning vid lägre (<0.6%) mekaniska töjningsomfång (livslängder över 1000 cykler till brott). Vid högre töjningsomfång uppvisar AISI 310H bättre cyklisk duktilitet och högre ligslängd. Emellertid uppvisar Sanicro 25 en klar fördel i fråga om styrka vid både låga och höga temperaturer.
- Exponering vid 800°C främjar bildandet av utskiljningar längs korngränserna i Sanicro 25. Dessa partiklar bidrar till bildandet av porer och mikrosprickor under dragbelastning, som i sin tur leder till en minskning av duktiliteten. Liknande skademekanismer kan även ses efter TMF provning.

Rapporten kommer att uppdateras ytterligare en gång när all provningen är genomförd.

Nyckelord: Termomekanisk utmattning, Austenitiska Rostfria Stål, Kryp och Draghållfasthet, Inverkan av åldring

Summary

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.

The report will be updated when the testing has been completed.

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

Table of contents

1 Introduction

1.1 Background

One of the main goals for KME during the program period 2010-2013 is to verify that steam temperatures can be increased by minimally 50°C in new power plants with biofuel or waste fractions as fuel. To avoid the risk of cracking due to the increased steam data, studies are necessary to establish the mechanisms that have most effect on 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.

Furthermore, the changes in demand, and competition within the power generation market (e.g. due to the increasing use of solar and wind power) forces many power plants to also operate under more cyclic conditions and thus more fatigue load cycles are generated. 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 behavior 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 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.

1.2 Description of the research field

Constraint of free thermal expansion and contraction is an intrinsic ingredient of the thermally induced fatigue process, which is of interest to reproduce on a laboratory scale during thermomechanical fatigue (TMF) testing. The most common types of TMF cycles are illustrated in Figure 1. The in-phase (IP) and the out-of-phase (OP) cycles represent the cases when external loads or temperature gradients are present within a component during steady-state operation. On the other hand, the clockwise-diamond (CD) and the counter-clockwise-diamond (CCD) cycles simulate the transient effects that can occur during start-up or shut-down, due to for instance different heating or cooling rates of thin versus thick sections of a component. During a TMF loading, the primary damage mechanisms that can play a role in metals are fatigue, environmental and creep damage. These damage mechanisms may act alone or in combination with each other, based on operating conditions such as strain range levels, strain rate, length of dwell times or temperature intervals.

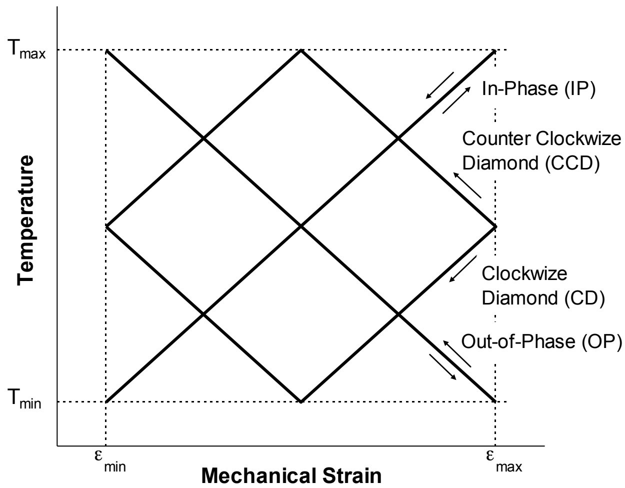


Figure 1: Schematic illustration of different types of TMF-cycles

In austenitic stainless steels, the activated damage mechanism can alter the cracking behaviour from intergranular for creep dominant conditions to that of transgranular in fatigue dominant conditions. In recent years, numerous research studies have been performed focusing mainly on non-stabilized grades (304 and 316L) subjected to TMF loading under varying strain amplitudes, environment and temperature conditions, see references [1–9].

In the high temperature range, a strong difference between IP and OP loading is typically seen, where IP loading is much more detrimental than OP cycling. One explanation to this behaviour is that creep damage exclusively develops under IP conditions because of the combination of high temperatures and tensile stresses that favours the formation of wedge-type cracks at grain boundary triple points and voids at grain boundaries.

In addition most austenitic Fe and Ni base materials are susceptible for the degradation mechanism called ”relaxation cracking” at temperatures between 550 and 750°C. The brittle failures are always located in cold-formed areas or in welded joints and are mostly addresses within 1 year of service [10,11]. Many different names can be found in the literature for this phenomenon (stress relaxation cracking, stress-induced cracking, reheat cracking or stress-assisted grain boundary oxidation SAGBO) but the main characteristics are the same. Typically, cracks with a brittle appearance are also in this case located along grain boundaries and in front of the cracks small isolated cavities are present. Some times also a metallic filament is present on the cracked grain boundaries [10]. It is very likely that this type of failure mechanism will be active during thermomechanical fatigue 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. It can also be believed that ageing play an important role. Many austenitic materials show an age hardening behaviour at temperatures between 550 and 750°C where many very fine particles precipitate within the grains and as a consequence the hardness level can increase significantly which is good from a pure fatigue point of view. On the other hand, when this occur the grain boundaries lose ductility, which in turn causes the metal to crack along the grain boundaries when strained and thus this can be bad from a creep perspective. The effect of long term ageing on the thermomechanical fatigue behaviour is however not very well studied, especially if also significant dwell time relaxation is included in the TMF cycle. It can also be expected that the influence from ageing will differ significantly between an IP and an OP-TMF cycle.

1.3 Research task

The project plan consist of the following three parts:

Part 1: Thermomechanical fatigue testing

Thermomechanical fatigue testing will be performed on several different austenitic stainless steels. The alloys of interest are Sanicro 25, Alloy 800HT, Sanicro 28, 347H and Esshete 1250 and 310H. The materials represents a mix of well established materials for this type of application and new potentially better materials. The resistance to TMF failure for both an IP and an OP TMF cycle will be analysed and compared for all materials. Later on in the project also long term aged material will be tested and the results will be compared to the virgin condition. 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.

Part 2: Long term ageing

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. At the chosen temperature these types of materials are in general very prone to precipitation of secondary phases leading to significant degradation of the materials mechanical properties.

Part 3: Investigation of deformation and damage mechanisms

The deformation and damage mechanisms will be investigated using Scaning Electron Microscopy (SEM).

1.4 Goal

Project goal

The purpose of this project is to evaluate and rank the susceptibility to thermomechanical fatigue damage of several austenitic materials. The underlying mechanisms will be studied in order to better take the effect of temperature and straining history into account from a component perspective.

Contribution to KME’s goal

Especially this project address the following goal of the KME-program: ”Conduct laboratory studies to establish the mechanisms that have most effect on the mechanical service life of materials in relation to new demands on them when more effective electricity production results in higher steam pressures and temperatures in plants using renewable (complicated) fuels.”

1.5 Project organisation

The project KME-521 has been conducted in collaboration with the division of engineering materials at Linköping University and Sandvik Materials Technology. There has also been some coordination and cooperation with the already running KME-501 project.

Project leader: Johan Moverare, LiU

Project partners: Guocai Chai, Sandvik MT
Jan Högberg, Sandvik MT
Raveendra Siriki, Sandvik MT
Tommy Sand, Sandvik MT
Mattias Calmunger, LiU
Sten Johansson, LiU

Reference group: Göran Sjöberg, Chalmers
Pamela Henderson, Vattenfall
Annika Stålenheim, Vattenfall
Håkan Brodin, Siemens

The project has been financed by KME with in kind contribution from Sandvik Materials technology. The initial cost plan, as stated in the application, can be found below. A final cost accounting will be given separately and is not included in this report.

	Year 1 2012-11-01 to 2013-03-31	**Year 2** 2013-04-01 to 2014-03-31	**Total** 2012-011-01 to 2014-03-31
In kind contribution			
Sandvik MT	365	639	1004
Costs at LiU			
Salary	101	206	307
Workshop	25	25	50
Equipment	50	75	125
IT & Software	3	5	8
OH	59	105	164
Financing:			
KME	243	426	669

2 Methods and Test matrix

In this section the different materials and test methods used in the project is presented in more detail together with the test matrix proposed at the start of the project.

2.1 Materials

The following materials has been considered in the project; Sanicro 25, Alloy 800HT, Sanicro 28, AISI 347H, Esshete 1250 and AISI 310H. The materials represents a mix of well established materials for power plant applications and new potentially better materials. The chemical composition is listed in

Table 1: Chemical composition of materials considered in the project

	C	Si	Mn	Cr	Ni	Mo	Ti	Al	W	Co	V	Cu	N	Nb	B	Fe
Sanicro 25	≤0.1	0.2	0.5	22.5	25				3.6	1.5		3.0	0.23	0.5		Bal
Alloy 800HT	0.07	0.6	0.6	20.5	30		0.5	0.5								Bal
Sanicro 28	≤0.02	≤0.6	≤2.0	27	31	3.5						1.0				Bal
AISI 347H	0.05	0.6	1.7	17.5	10									0.7		Bal
Esshete 1250	0.1	0.5	6.3	15	9.5	1.0					0.3			1.0	0.005	Bal
AISI 310H	0.06	≤0.75	1.5	24.5	21											Bal

Typical creep properties of the different materials can bee seen in Table 2. One can see that Sanicro 25 displays the best creep resistance while AISI 310H has the poorest creep resistance .

Table 2: Average creep properties, from data sheets provided on the web by Sandvik Materials Technology

	Creep rupture strength for 100 000 h [MPa]			
	600°C	700°C	800°C	900°C
Sanicro 25	230	95	25	
Alloy 800HT	127	57	27	13
Sanicro 28	146	62		
AISI 347H	115	48	16	
Esshete 1250	199	54		
AISI 310H	56	24	11	4

2.2 Methods

The test methods used in the project is mainly Thermomechanical fatigue (TMF) testing and Scanning Electron Microscopy (SEM). A few tensile tests have also been performed in order to evaluate the effect of ageing on the material.

2.2.1 TMF testing

TMF tests can be performed with an arbitrary phase shift (φ) between the temperature and the mechanical loading as seen in Figure 1. In this study, in-phase (φ=0°) tests is the main cycle type to evaluate the materials. However a few out-of-phase (φ=180°) tests have also been performed. All tests were conducted using closed loop servo-hydraulic testing machines from Instron. Induction heating and forced air cooling are used in order to cycle the temperature. The minimum temperature in all tests was 100°C while the maximum temperature was 800°C. Strain was measured by an axial extensometer and all tests were done in mechanical strain control (i.e. with a fixed total strain range compensated for thermal expansion $\Delta\varepsilon = \varepsilon_{max} - \varepsilon_{min}$). The strain ratios where always R = 0 for the IP tests and R = -∞ for the OP tests. The dwell time is normally 5 min in each cycle. Heating and cooling rates were set to 5°C/s.

The specimen geometry used for the initial tests on Sanicro 25, AISI 347H and AISI 310H can be seen in Figure 2(a). This geometry was first used for the 2 first test series on Sanicro 25 and AISI 310H. During the third test series on AISI 347H significant buckling occurred. When the specimens from the two first test series were re-examined, these specimens also revealed some buckling, but not to the same degree as for the tests on AISI 347H. During an IP TMF test, the specimens are subjected to significant compressive stresses at the low temperature end of the cycle. After the 3:rd test series it was decided to modify the specimen in order to avoid the risk for buckling. The modified specimen geometry can be seen in Figure 2(b). Due to the buckling all tests on AISI 347H is excluded in this report. For the other two materials it is believed that the buckling only hade a minor effect on the TMF-life.

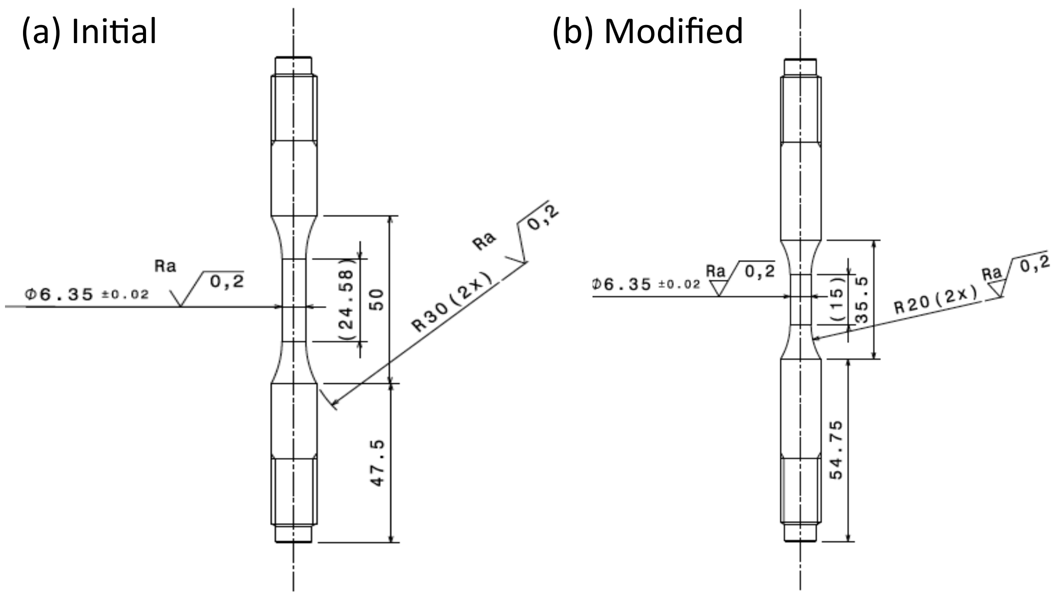


Figure 2: (a) Initial specimen genometry, (b) Modified specimen geometry to prevent buckling.

2.2.2 Tensile testing

All tensile tests have been performed at room-temperature using an electro mechanical tensile testing machine from Instron. The initial strain rate in the tests were 0.02%/s. Some of the tests were interrupted after 10% or 30% plastic deformation. They were then removed from the testing machine and furnace exposed at 650°C or 800°C for 100 hours. After the high temperature exposure the specimens were re-tested in order to reveal the effect of long term ageing on the mechanical properties. This type of investigation has only been performed for Sanicro 25.

2.2.3 Microscopy

After the tests, most specimens were investigated by stereomicroscopy before they were cut parallel to the loading direction for further investigation by scanning electron microscopy (SEM). The SEM samples were prepared by grinding and mechanical polishing, but no samples were etched. Orientation imaging microscopy (OIM) has also been performed using an electron back-scattering diffraction (EBSD) system. By using EBSD analysis it is possible to investigate the occurrence of recrystallization during the TMF-tests.

2.3 Test matrix

For each of the 6 materials, 5 tests are planed in each condition (virgin and aged). The 5 tests for each material and condition will be performed at different mechanical strain ranges with the aim to give a fatigue life in the range between 100 and 3000 cycles to failure. The test matrix and it's current status is listed below.

Virgin material	
Sanicro 25	All 5 tests completed
AISI 310H	All 5 tests completed
AISI 347H	5 tests completed Due to problems with buckling the results are not included in this report
Alloy 800HT	2 tests completed
Esshete 1250	Specimens available and will be tested during spring 2014.
Sanicro 28	Sandvik has not been able to deliver this material
Aged material	
Sanicro 25	The tests on aged material will not be possible to complete within the current program period and is therefore proposed as an activity for the next programme period of KME.
AISI 310H	
AISI 347H	
Esshete 1250	
Alloy 800HT	
Sanicro 28	

3 Results

3.1 Tensile testing

The aim of the tensile tests has been to evaluate the effect of thermal exposure on the mechanical properties of Sanicro 25. Prestraining of the material was performed as interrupted tensile tests at room temperature. The tests were interrupted after 10% or 30% plastic deformation and the samples were furnace exposed at 650°C or 800°C for 100 hours. The samples were then retested to failure. For all test conditions three identical tests were performed. The results can bee seen in Figure 3.

One can see that the ageing at 650°C has no significant influence on the results. When ageing is performed at 800°C one can see a tendency of recovery due to the heat treatment but this is somewhat compensated by the increase in the hardening rate after yielding the second time which gives more or less the same ultimate tensile strength in all samples independent of the history. The most significant impact from ageing seems to be a decrease in ductility when ageing is performed at 800°C. This is very clear for the sample with 10% pre strain where the total elongation before fracture is only 30% compared to the virgin material.

3.2 TMF testing

Thermomechanical fatigue testing has been performed on four alloys so far. Due to problems with buckling the results for AISI 347 will not be included in this report. Furthermore, since only two tests have been performed on Alloy 800HT so far, these results are not included either. A new update of this report with all tests included is planed before the summer 2014.

All tests are performed in mechanical strain control and the number of cycles to failure for a given applied mechanical strain range can be seen in Figure 4. For the strain ranges tested one can see a clear advantage for AISI 310. One test on AISI 310H differs from all others and should be questioned; this will be investigated and reported on in the next update of this report. The difference between the two alloys decreases with decreasing strain range and is essentially the same for strain ranges lower than 0.6%. However, there is also a significant difference in stress strain response between the two alloys during thermomechanical fatigue cycling. This is illustrated in Figure 5 where the stress-strain loop for the midlife cycle ($N_f/2$) of the IP tests between 100-800°C and a mechanical strain range of $\Delta\varepsilon_{mech}$ = 0.8% can be seen. Both the compressive stress at low temperature and the tensile stress at high temperature is higher for Sanicro 25 indicating that both the low temperature yield strength and the creep properties at high temperature is higher for this alloy.

By using the information from the mid-life cycle it is possible to also plot the stress range and the inelastic strain range as a function of cycles to failure. The results can be seen in Figure 6 and Figure 7 respectively. The inelastic strain range is measured as the width of the hysteresis loop at zero stress.

For an equivalent number of cycles to failure, the figures indicate that AISI 310H can withstand a higher degree of inelastic deformation while Sanicro 25 can with stand a higher stress range.

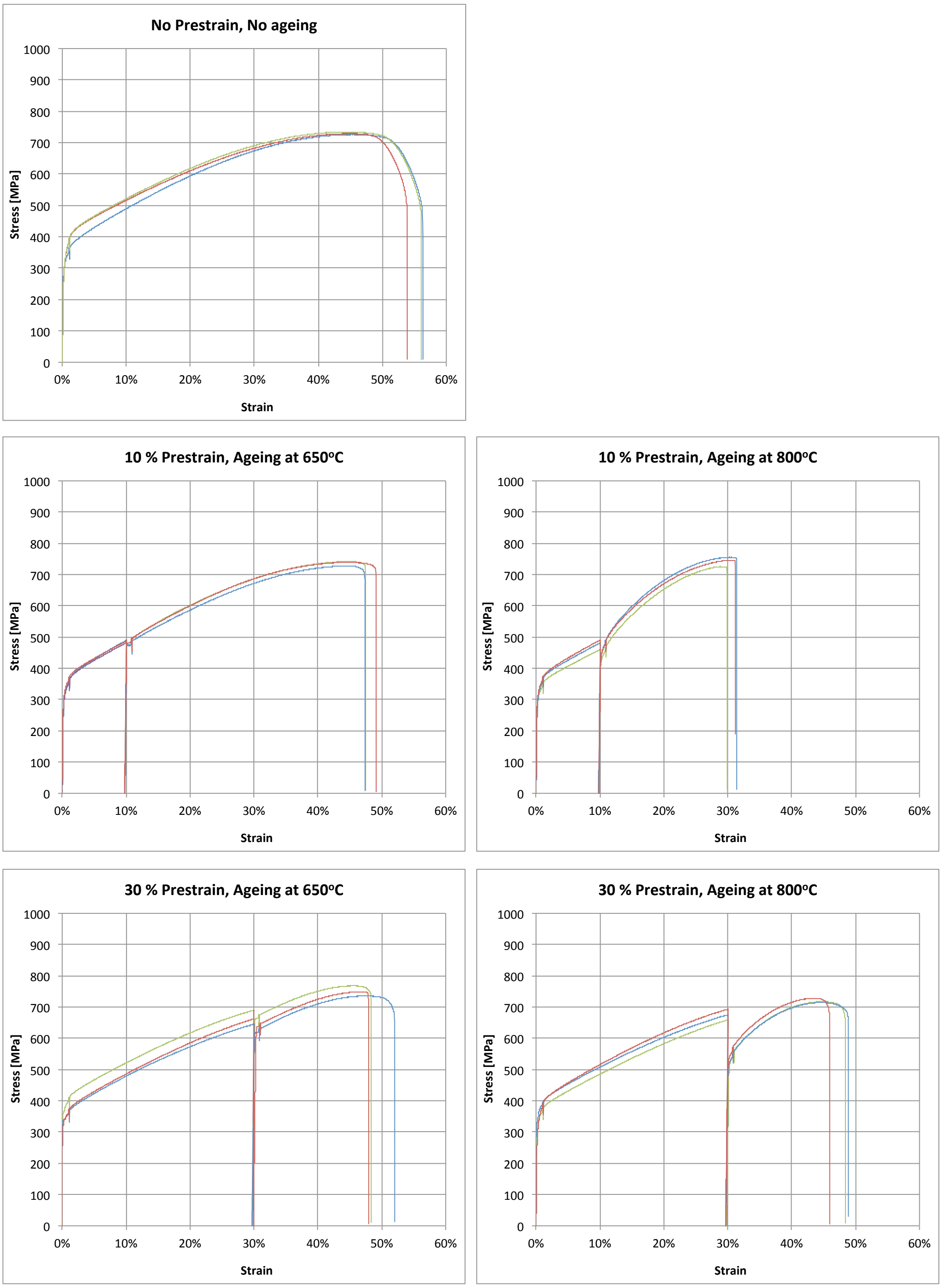


Figure 3: Results from tensile testing of Sanicro 25 showing the effect of prestraining and ageing. All tensile tests performed at room temperature. Ageing time is 100 hours. For all test conditions three identical tests were performed, represented by the different lines in each graph.

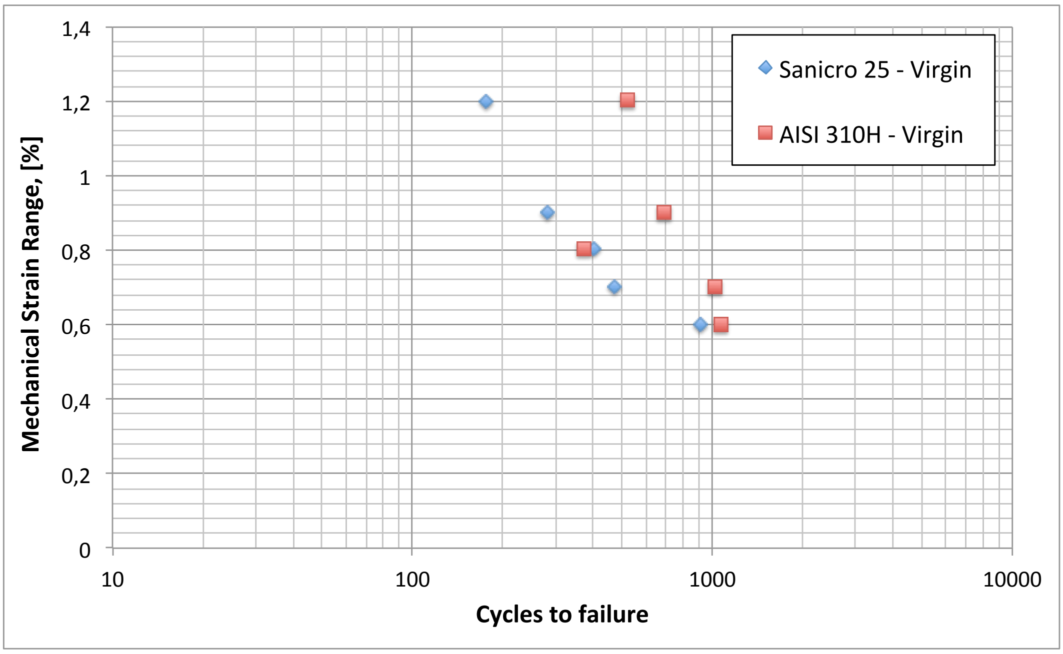


Figure 4: Mechanical strain range versus number of cycles to failure for out-of-phase thermomechanical fatigue with a maximum temperature of 800°C.

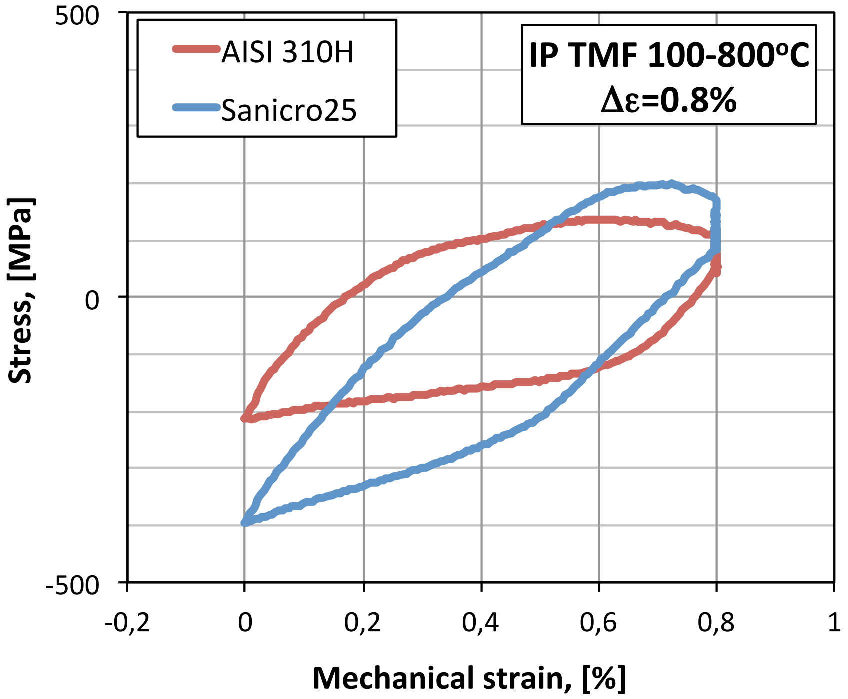


Figure 5: Mid-life stress strain loop shapes for AISI 310H and Sanicro 25

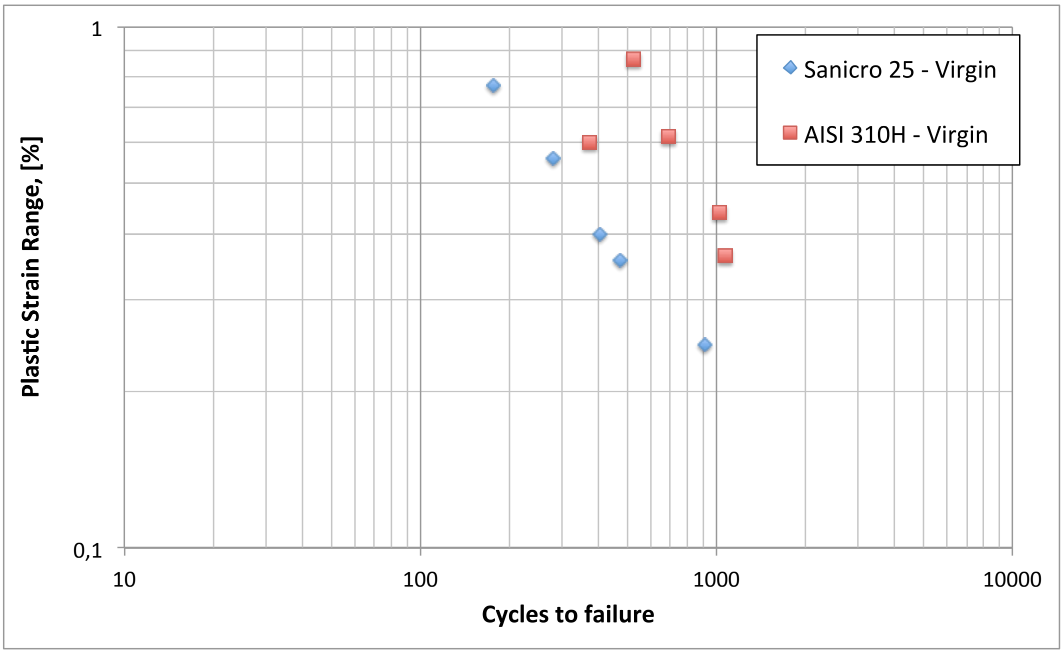


Figure 6: Plastic strain range versus number of cycles to failure for out-of-phase thermomechanical fatigue with a maximum temperature of 800°C.

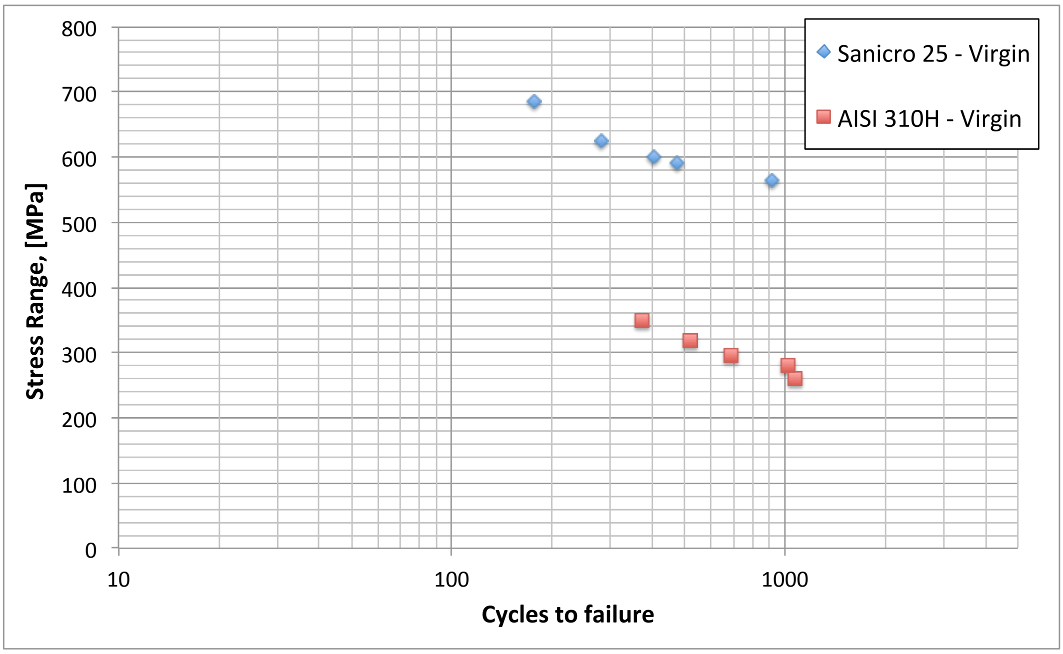
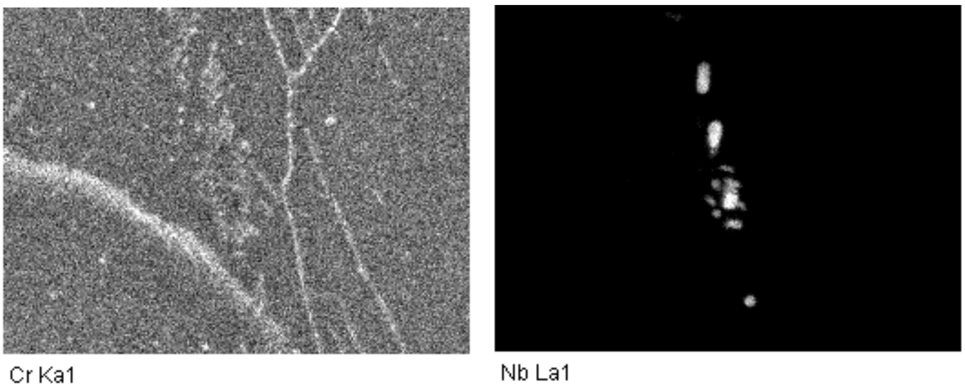


Figure 7: Stress range versus number of cycles to failure for out-of-phase thermomechanical fatigue with a maximum temperature of 800°C.

3.3 Microscopy of Sanicro 25 after tensile testing

Some initial microscopy work has been performed on Sanicro 25 after prestraining and ageing at 800°C. After tensile testing, extensive void formation and microcracking can be seen as shown in Figure 8a. The location of the voids and microcracks are mainly along grain boundaries and along planar features within the grains, which most likely are slip bands formed during the initial prestraining. Both the grain boundaries and the slip lines are decorated with small Cr-rich precipitates, as seen in Figure 8b. In addition it is common to see crack formation at some Nb-rich precipitates. The size of the Nb-rich precipitates indicate that they have been present in the material already in the virgin condition. On the other hand, the Cr-rich precipitates have probably nucleated and/or grown during the ageing at 800°C.

(a)



(b)

Figure 8: Microsctructure after tensile testing of Sanicro 25 in prestrained (30%) and aged (800°C) condition. (a) Back scatter image from SEM, (b) EDS analysis showing the presens

3.4 Microscopy of Sanicro 25 after TMF testing

Some initial microscopy has also been performed on Sanicro 25 after thermomechanical fatigue testing. In the upper part of Figure 9 one can see the band contrast from EBSD measurements; the dark grey appearance corresponds to a lower quality pattern, which can results from either grain boundaries or internal distortion within the grains due to plastic deformation. In the lower part of Figure 9, the degree misorientation within the grains is illustrated by colouring all neighbouring points with an orientation difference between 1 and 10°C in white. High angle grain boundaries are coloured in black.

One can notice that the deformation induced during thermomechanical fatigue is rather high but seems to be very uniformly distributed within the material.

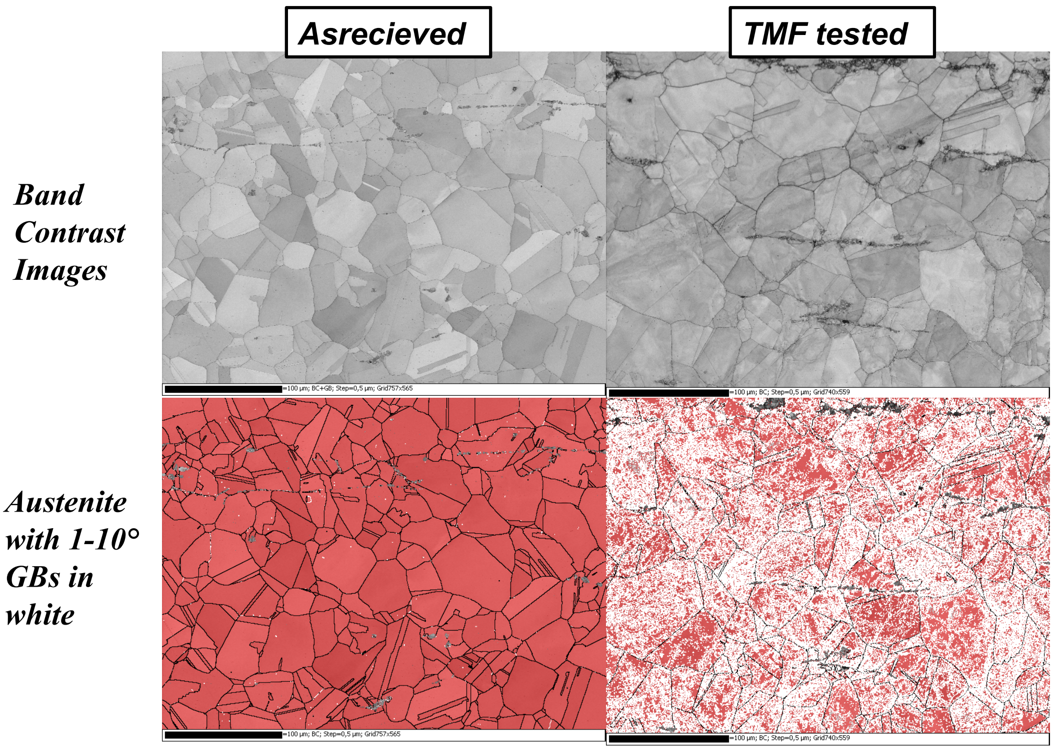


Figure 9: EBSD results showing the difference in band contrast and degree of misorientation between as received and TMF tested material.

In slightly higher magnification of the TMF tested material, see Figure 10, it is possible to notice crack formation at the interfaces between precipitates and grain boundaries. Some of the precipitates are Nb-rich, as previously seen also for the aged tensile tested material.

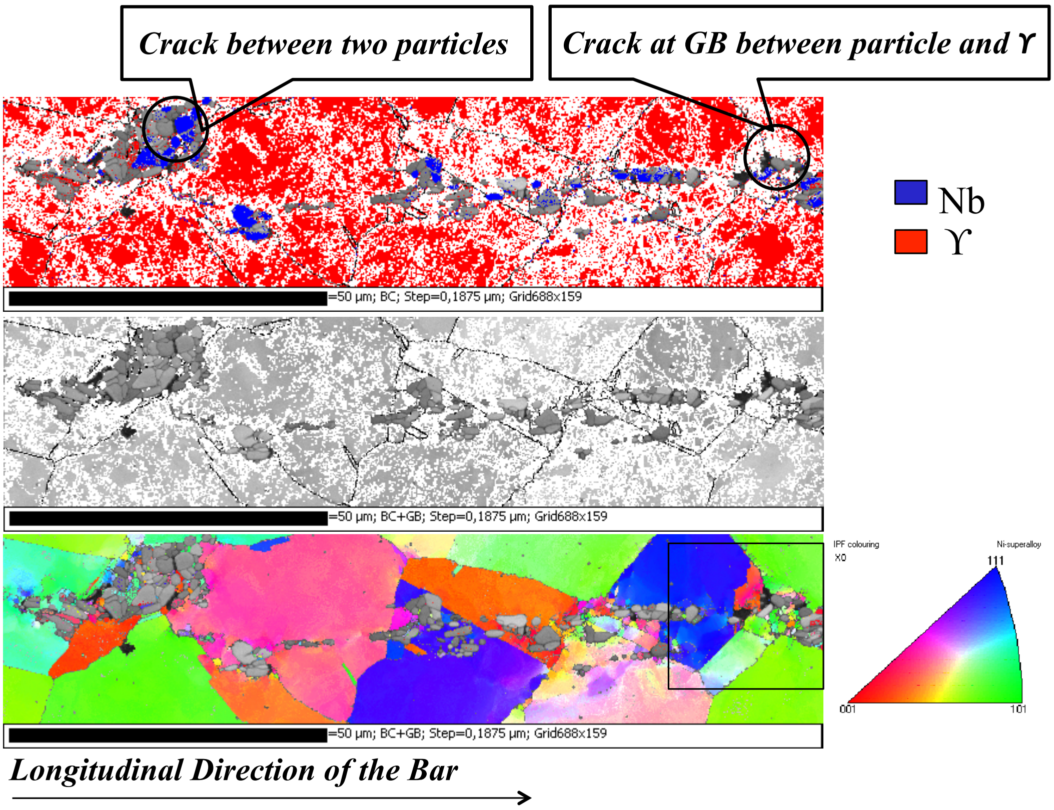


Figure 10: EBSB results showing crack formation at grain boundaries and particles.

4 Analysis of the results

As for most materials, high strength is beneficial for fatigue resistance only if ductility is preserved. If strength is increased on the expense of ductility, nothing is generally gained with respect to the overall fatigue resistance of the material. This is of course not a universal law but rather a good rule of thumb. However, the comparison of TMF resistance between Sanicro 25 and AISI 310H clearly demonstrate this fact, see Figure 4. It is however important to realize that high strength is often beneficial for real components for other reason. Good resistance to creep will for instance promote dimensional stability of the components. One should also realize that the dwell time in the TMF-test is only 5 min in this study while the dwell time is much longer for real components during service. In a strain-controlled test, it is often beneficial with good creep resistance when the dwell time is increased.

Thus it can, based on the findings so far, still be assumed that Sanicro 25 has superior mechanical properties compared to AISI 310H in power plant applications. However, the studies performed so far are very limited and some of the planed work remains to be done. It is important to further investigate how the ductility and fatigue resistance is preserved after long term exposures at elevated temperature. At the time for the writing of this report, Sandvik MT subjects several austenitic stainless steels to furnace exposures. These samples will later on be TMF tested in the continuation of this project. However, the tensile tests on prestrained and aged material gives some indication that a decrease in ductility can be expected, especially when the material is exposed at 800°C, see Figure 3. If and how much this will effect the thermomechanical fatigue resistance remains to be investigated. It is also interesting to see that the damage mechanisms seen in the prestrained and and aged tensile tests are essentially the same as seen in the TMF tested material, that is void formation and microcracking at precipitates along the grain boundaries.

5 Conclusions

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 demonstrate an advantage in strength and 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.

Further testing is needed in order to determine the effect of ageing on the thermomechanical fatigue resistance.

6 Goal fulfilment

The purpose of this project is to evaluate and rank the susceptibility to thermomechanical fatigue damage of several austenitic materials. The underlying mechanisms will be studied in order to better take the effect of temperature and straining history into account from a component perspective.

This project was the last one to be accepted in this fifth stage of the material technology research programme KME. The board accepted the project proposal in October 2012 and the project agreement was signed by all partners in March 2013. The first set of test bars of Sanicro 25 was also delivered to LiU at that time. Thus, the time frame to complete the project within the current stage of KME was very limited and so far it has not been possible to fulfil the goals for the project. However, the projects have delivered some interesting results and the plan is to continue the project in order to fulfil the goals.

The plan is to complete all tests on virgin material before summer 2014. This will result in an updated final report for KME-521. The tests on aged material will not be possible to complete within the current program period and is therefore proposed as an activity for the next programme period of KME.

7 Suggestions for future research work

As indicated in the previous section the project have more or less just started and the plan is to continue in the next stage of the KME programme. Several virgin materials remains to be tested together with the long term aged material. Parallel to this the microscopy work will also continue.

8 Literature references

[1] Christ H-J. Effect of environment on thermomechanical fatigue life. Mater Sci Eng A 2007;468-470:98–108.

[2] Majumdar S. THERMOMECHANICAL FATIGUE OF TYPE 304 STAINLESS STEEL. Am. Soc. Mech. Eng. Press. Vessel. Pip. Div. PVP, vol. 123, San Diego, CA, USA: ASME, New York, NY, USA; 1987, p. 31–6.

[3] Nagesha a, Valsan M, Kannan R, Bhanusankararao K, Bauer V, Christ H, et al. Thermomechanical fatigue evaluation and life prediction of 316L(N) stainless steel. Int J Fatigue 2009;31:636–43.

[4] Kuwabara K, Nitta A. Thermal-mechanical low-cycle fatigue under creep-fatigue interaction on type 304 stainless steel. Fatigue Fract Eng Mater Struct 1979;2:293–304.

[5] Remy L. Fatigue and thermomechanical fatigue at high temperature. Encycl Mater Sci Technol 200AD;3:2868–79.

[6] Shi H-J, Wang Z-G, Su H-H. Thermomechanical fatigue of a 316L austenitic steel at two different temperature intervals. Scr Mater 1996;35:1107–13.

[7] Zamrik SY, Davis DC, Firth LC. Isothermal and thermomechanical fatigue of type 316 stainless steel. ASTM Spec. Tech. Publ., vol. 1263, 1996, p. 96–116.

[8] Zauter R, Christ HJ, Mughrabi H. Some aspects of thermomechanical fatigue of AISI 304L stainless steel: Part I. creep- fatigue damage. Metall Mater Trans A 1994;25:401–6.

[9] Zauter R, Petry F, Christ H-J, Mughrabi H. Thermomechanical fatigue of the austenitic stainless steel AISI 304L. ASTM Spec. Tech. Publ., ASTM,Philadelphia, PA, United States; 1993, p. 70–90.

[10] Van Wortel H. Control of relaxation cracking in austenitic high temperature components. Corros. 2007, Nashville, TN; United States: NACE International; 2007, p. 074231–0742313.

[11] Benac DJ, Olson DB, Urzendowski M. High-Temperature Stress Relaxation Cracking and Stress Rupture Observed in a Coke Gasifier Failure. J Fail Anal Prev 2010;11:251–64.

9 Publications

Due to the late start of the project no publications have been finalized so far. However, the project will continue and several publications are planed.

ELFORSK

SVENSKA ELFÖRETAGENS FORSKNINGS- OCH UTVECKLINGS - ELFORSK - AB

Elforsk AB, 101 53 Stockholm. Besöksadress: Olof Palmes Gata 31
Telefon: 08-677 25 30, Telefax: 08-677 25 35
www.elforsk.se