Heavy section austenitic stainless steel for the future header and piping material in high-efficient biomass-fired power plants

KME-801

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CONSORTIUM MATERIALS TECHNOLOGY

for development and demonstration of thermal energy processes

Acknowledgement

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Outline

- Background to the project
- Project goals
- Alloys
- Methods and selected results
- Publication list
- Summary

Background to the project

- Future power generation needs to be more efficient and flexible.
- Increasing demands on mechanical properties of the materials in critical components.
- Influence of cyclic high temperature deformation, creep and long-term service.
- Continuation of KME-501, 521 and 701.

Fuel

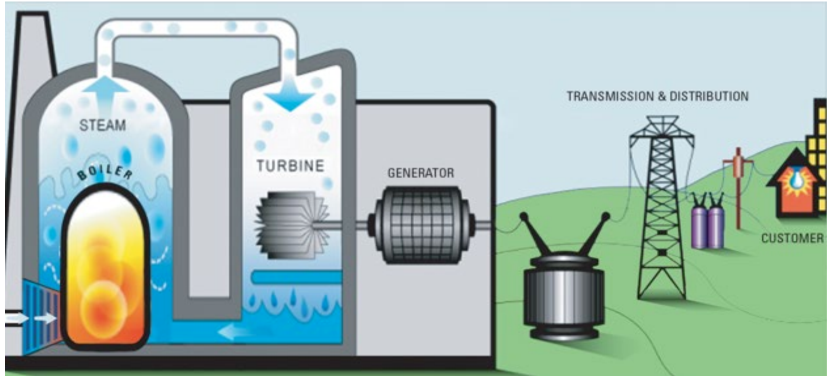


Image from Xcel Energy

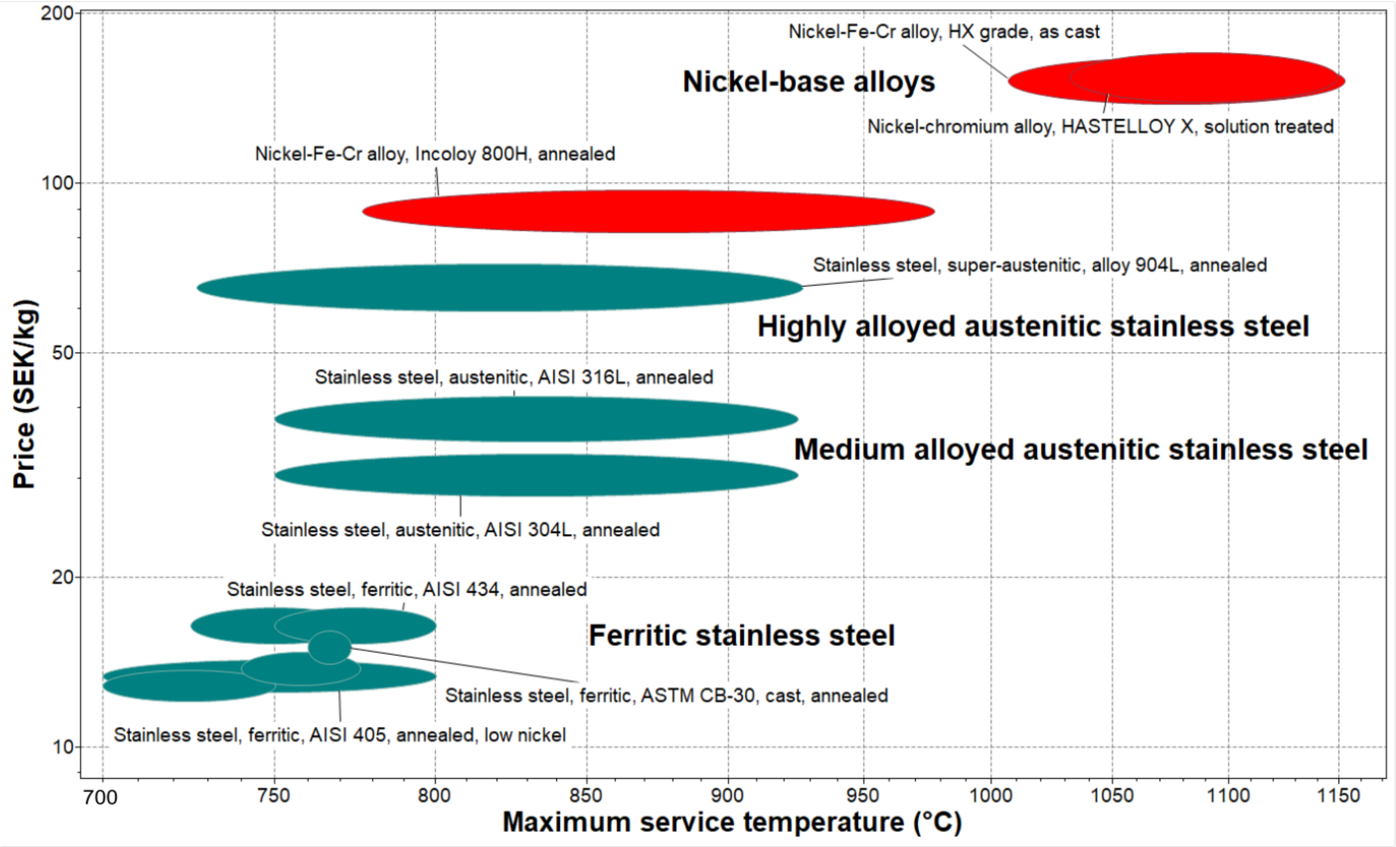
Gärdstadverken Linköping.
Photo Åke E. Lindman

Project goals

The main purposes of this project are to evaluate the mechanical behaviors for structure safety and integrity analysis, namely:

1. To **evaluate thermomechanical fatigue properties** of new materials of critical components for safety and life evaluation since the biomass-fired power plants can start/shutdown quite often during service for energy saving and flexibility purposes in the future.
2. To **evaluate the fatigue crack propagation behavior** of new materials used in safety and reliability considerations since the material of critical components can undertake low cycle fatigue during the service.
3. To **evaluate the creep resistance** of new materials used in safety and reliability considerations since the material of critical components can undertake creep during the service.
4. To **evaluate the structure stability and the toughness** of welded and aged material after long term service at high temperatures for safety analysis.
5. To **evaluate the new candidate material compared to currently used materials** using FE-models of the applications.

Alloys

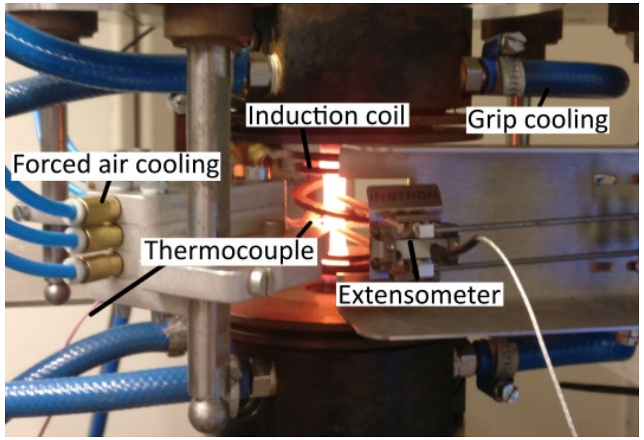


Difference in price [SEK/kg] vs. Maximum service temperature [°C] for some power plant materials (From GRANTA EduPack 2021).

Definition	Alloy	Approximate concentration of main alloying elements [wt%]
Nickel-base superalloy	Hastelloy X	Cr=22, Ni=47, Mo=9, Co=1.5, W=0.6, Mn=0.5, C=0.7, Si=0.5, Fe=17.5
Highly alloyed austenitic stainless steels	Sanicro 31HT (alloy 800HT)	Cr=20.5, Ni=30.5, C=0.7, Mn=0.6, Si=0.6, Ti=0.5, Al=0.5 Nb=0.5, Fe=bal
	Sanicro 25 (*)	Cr=22.5, Ni=25, W=3.6, Cu=3.0, Co=1.5, Mn=0.5, Nb=0.5, N=0.23, Si=0.2, C=0.1, Fe=bal
	Alloy 904L	Cr=20.5, Ni=25.5, Mo=4.5, Cu=1.5, Mn=1, Si=0.5, C=0.1, N=0.05, Fe=bal
	AISI 310M	Cr=25.4, Ni=19.2, Mn=0.84, Si=0.55, Mo=0.11, Cu=0.08, N=0.04, C=0.015, Ti=0.001, Fe=bal
Medium alloyed austenitic stainless steels	Esshete 1250 (*)	Cr=15, Ni=9.5, Mn=6.3, Nb=1, Mo=1, Si=0.5, V=0.3, C=0.1, Fe=bal
	AISI 304	Cr=18.3, Ni=10.3, Mn=1.4, Si=0.3, Cu=0.3, W=0.05, N=0.07, C=0.015, Fe=bal
	AISI 316L	Cr=17, Ni=12, Mn=1, Si=0.5, C=0.015, Fe=bal
Ferritic stainless steels	ASTM CB-30	Cr=19.5, Ni=1, Si=0.75, Mn=0.5, C=0.015, Fe=bal
	Grade 91	Cr=9, Mn=0.5, Mo=0.9, V=0.2, Si=0.35, C=0.1, Nb=0.1, N=0.05, Fe=bal

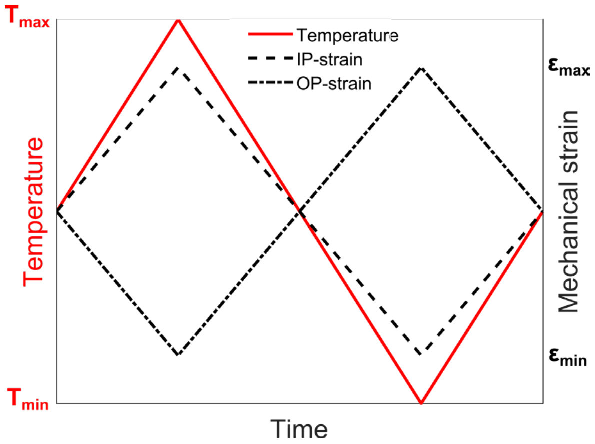
* Main investigated materials in this project.

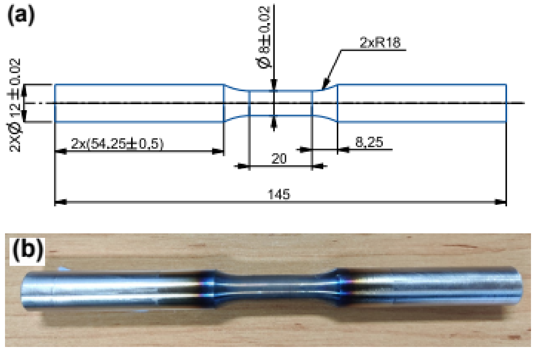
Methods and selected results



Thermomechanical fatigue testing (TMF)

- Cycle type
  - Phase-shift: Out-of-Phase (OP)
  - Heating/Cooling rate: 5°C/s
  - Maximum temperature: 600, **650**, 700 °C
  - Minimum temperature: 100°C
- Instron 8801 servo hydraulic test machine
  - Strain controlled
- Ageing for up to 10 000h at maximum temperature.

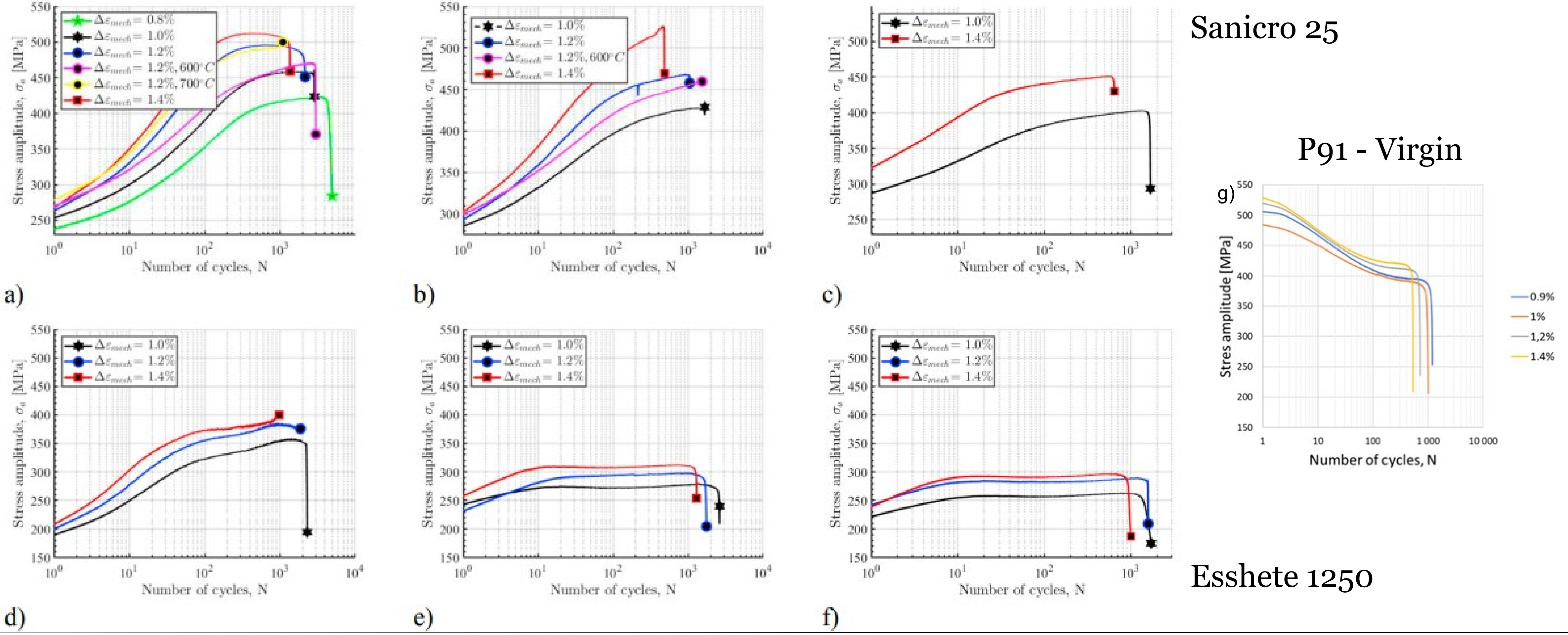




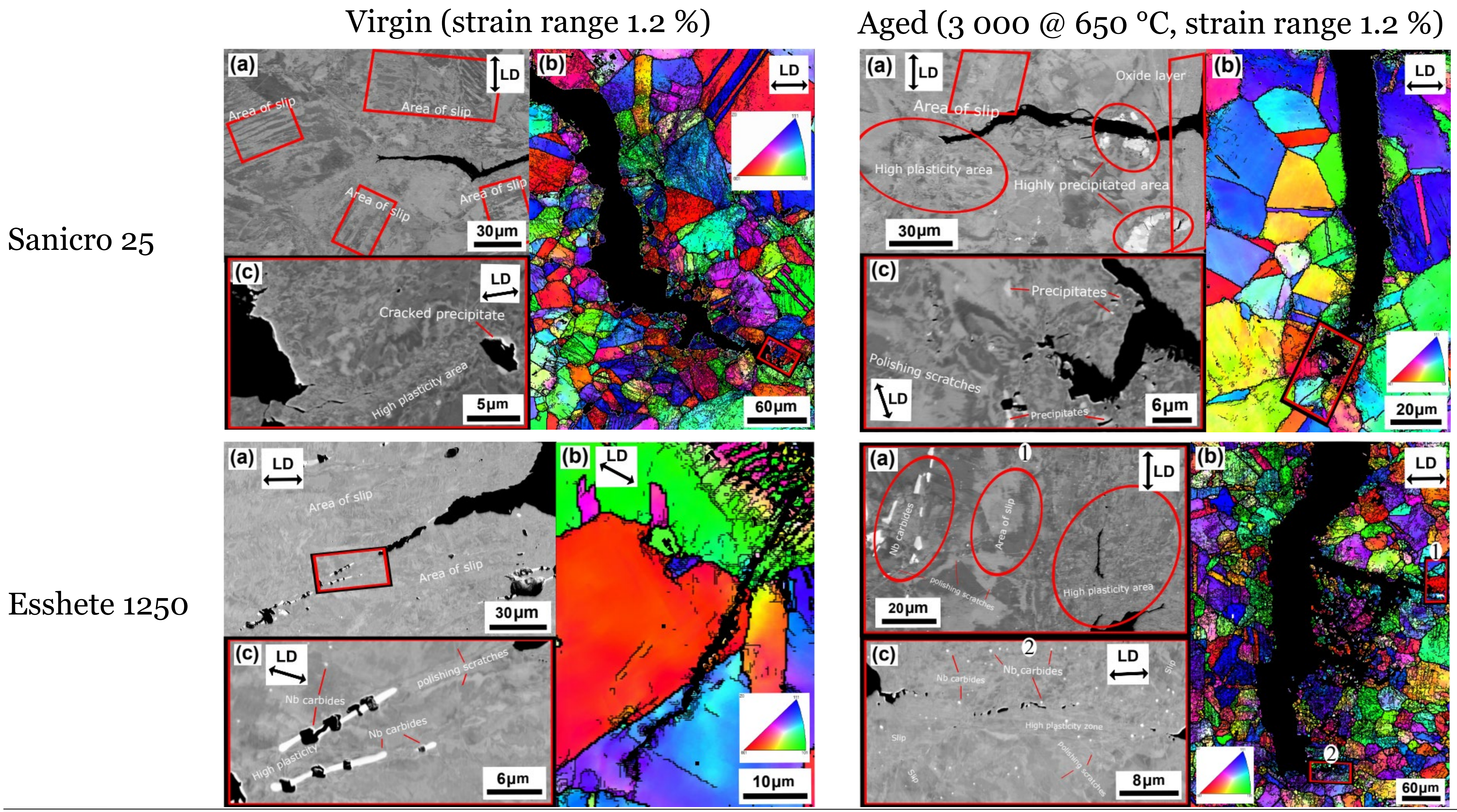
Upper right image: TMF test set up. Lower left image: Schematics of different TMF test cycles. Lower right image: The test specimen, (a) schematics (units in millimeters), (b) after testing of an OP-TMF Ehsshete 1250 specimen.

TMF – selected results

Virgin | Aged 3 000 h @ 650 °C | Aged 10 000 h @ 650 °C

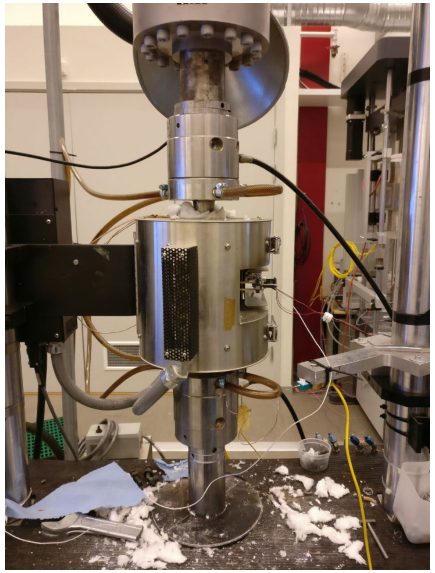


OP-TMF stress amplitude vs cycles curves for Sanicro 25 a) virgin, b) aged (3000 h at 650 °C) and c) aged (10 000 h at 650 °C) and Esshete 1250 d) virgin, d) aged (3000 h at 650 °C), f) aged (10 000 h at 650 °C) and P91 g) virgin.

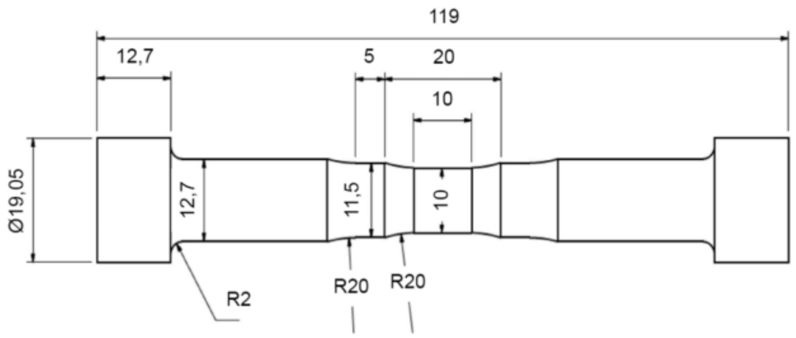


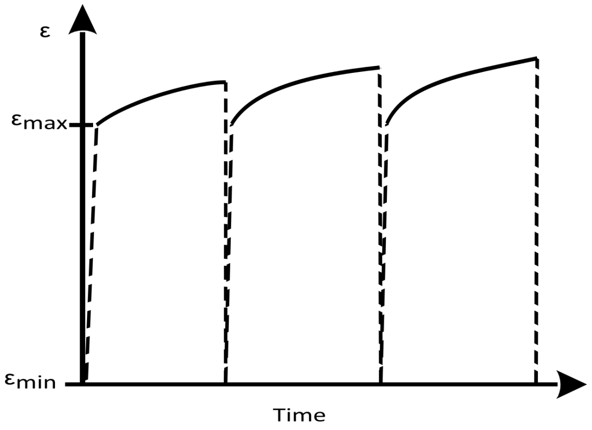
Micrographs of OP-TMF tested (strain range 1.2 %) Sanicro 25 and Esshete 1250, both virgin and aged. (a) SEM image deformation at crack tip area, (b) EBSD image of crack tip area and (c) SEM image higher magnification of crack tip. LD = loading direction.

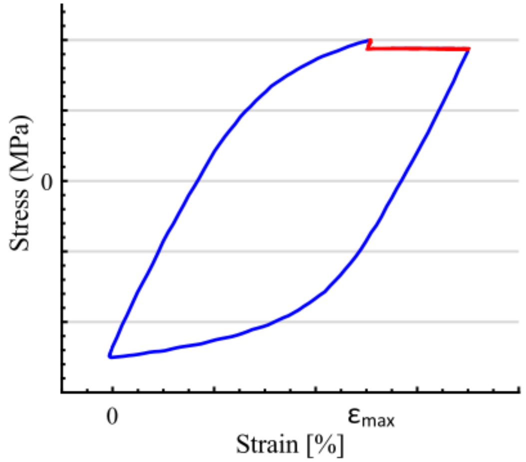
Low cycle fatigue (LCF) and creep testing



- Strain controlled fatigue part
- Load controlled dwell time
- Temperature: 700°C
- Dwell time: 300, 600 and 1 800 seconds
- Strain amplitudes: 0.25%-0.5%







Left image: Schematics of the test specimen (units in millimetres). Middle image: Sketch of the fatigue and creep test cycle. The solid lines represent the load controlled (creep) parts and the dotted lines represents the strain controlled (fatigue) parts. Right image: Sketch of a hysteresis curve, blue correspond to fatigue and red to creep loading.

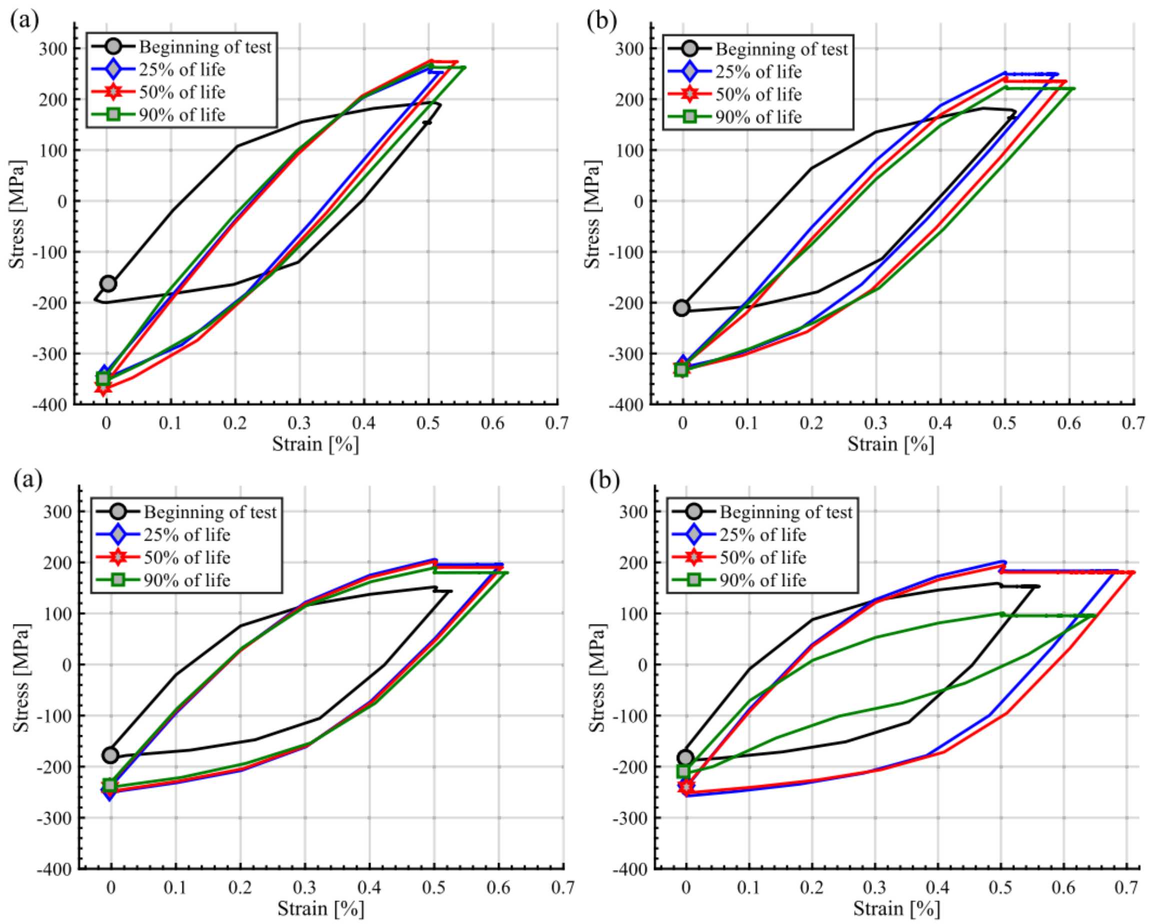
Creep and LCF – selected results

Dwell time: 300 s

1 800 s

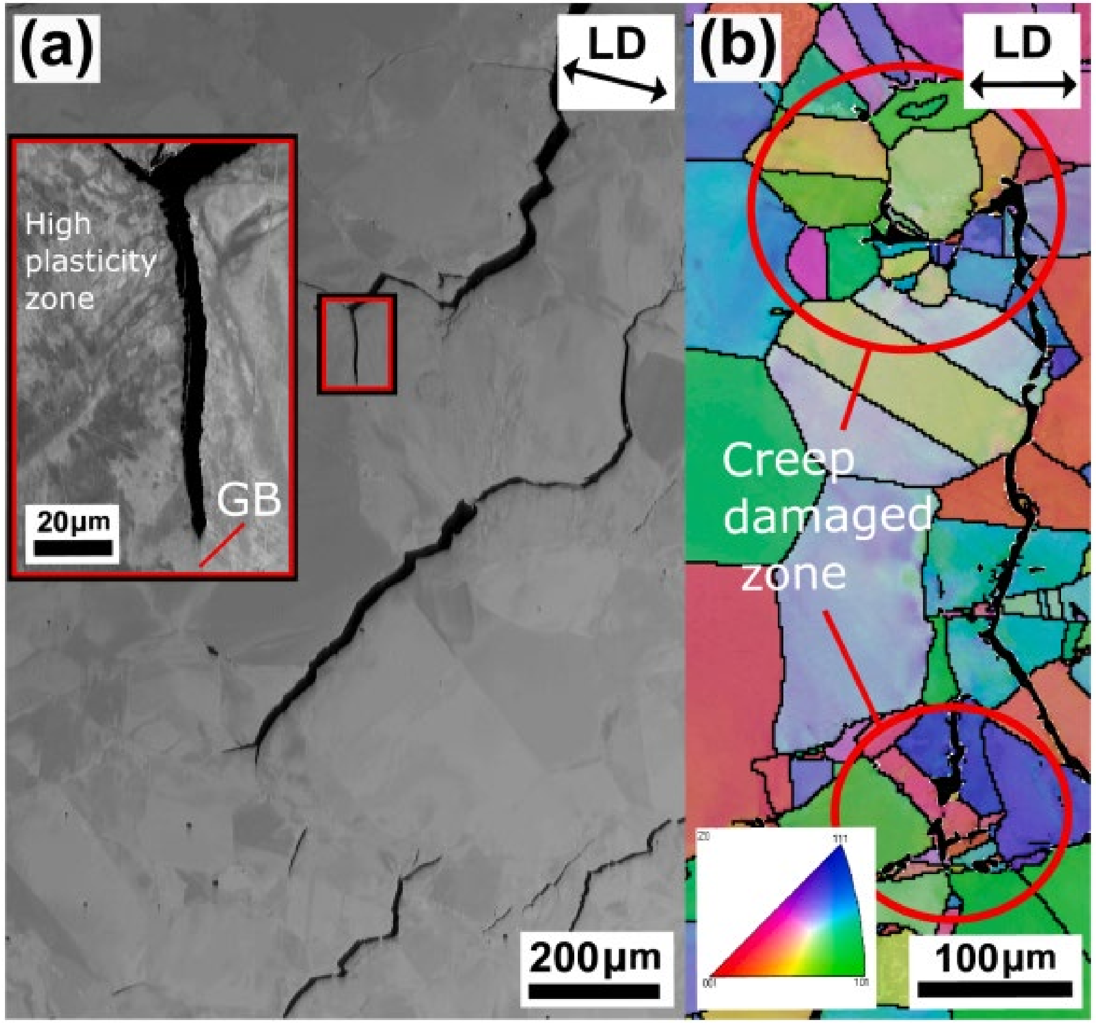
Sanicro 25

Esshete 1250

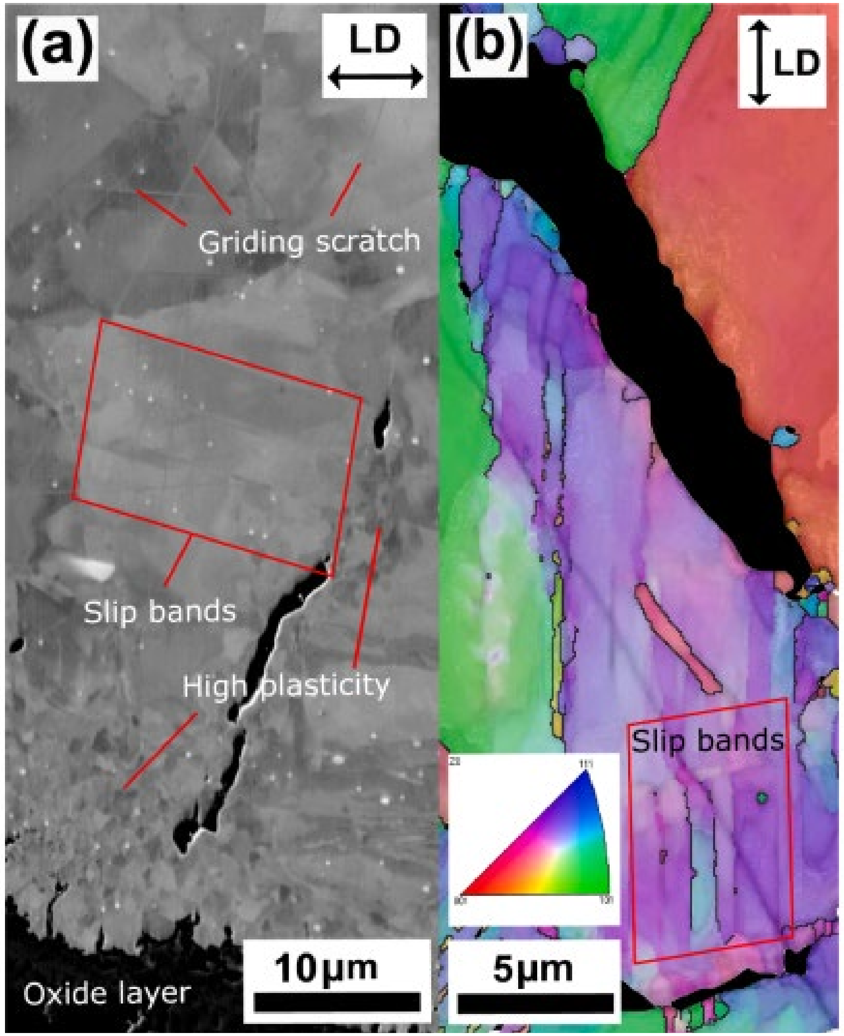


Hysteresis curves of Sanicro 25 and Esshete 1250 with dwell time of (a) t_d = 300 s, (b) t_d = 1800 s

Sanicro 25 with dwell time: 300 s

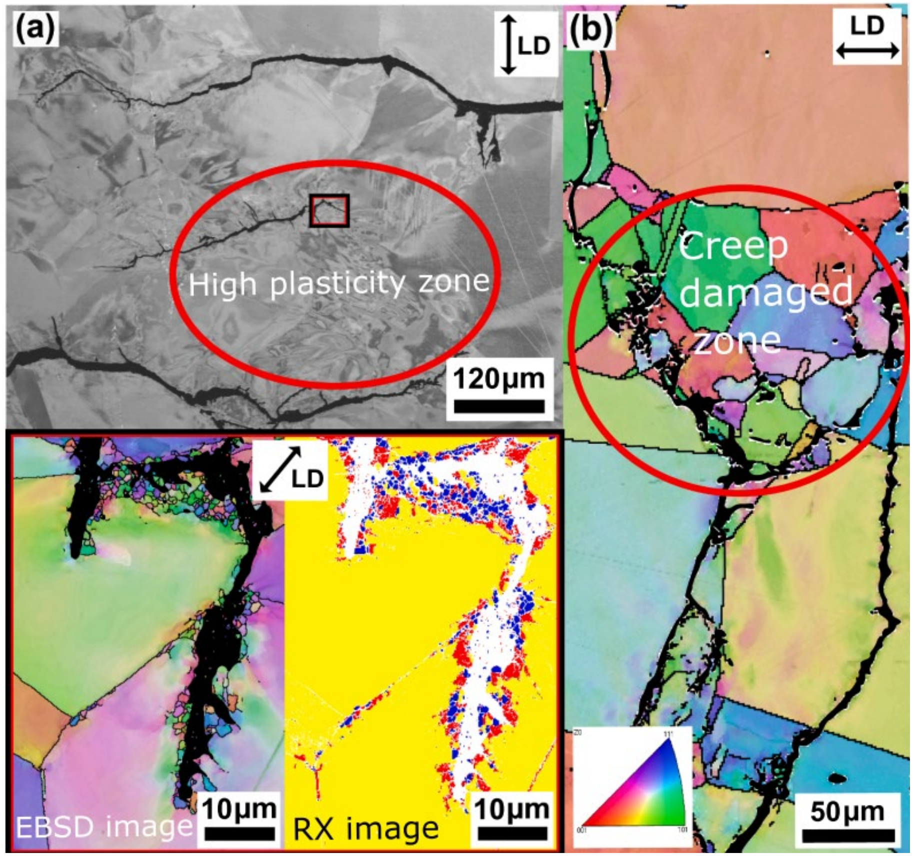


Esshete 1250 with dwell time: 300 s



Micrographs of Sanicro 25 and Esshete 1250 with dwell time 300 s: (a) crack propagation overview and for Sanicro 25 a zoomed in area of crack junction, (b) EBSD-image of crack propagation overview.

Crack propagation in Sanicro 25



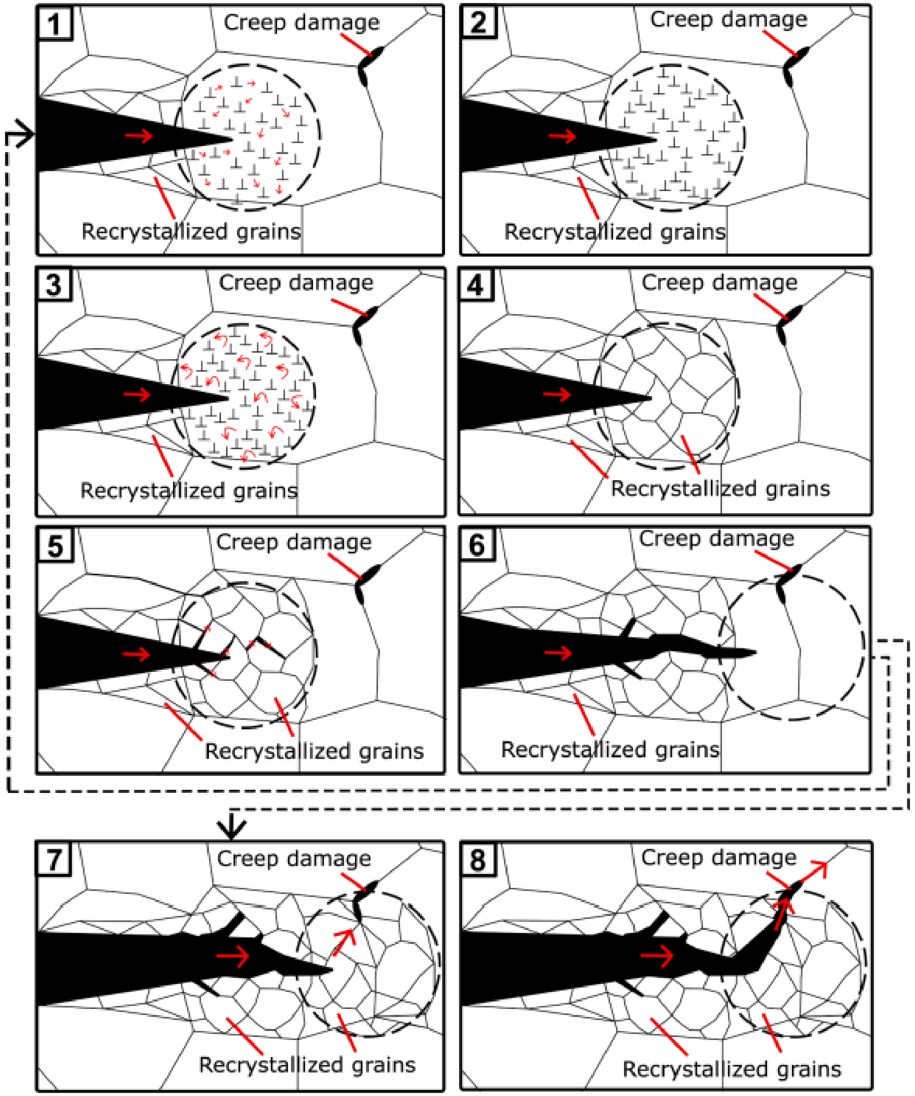
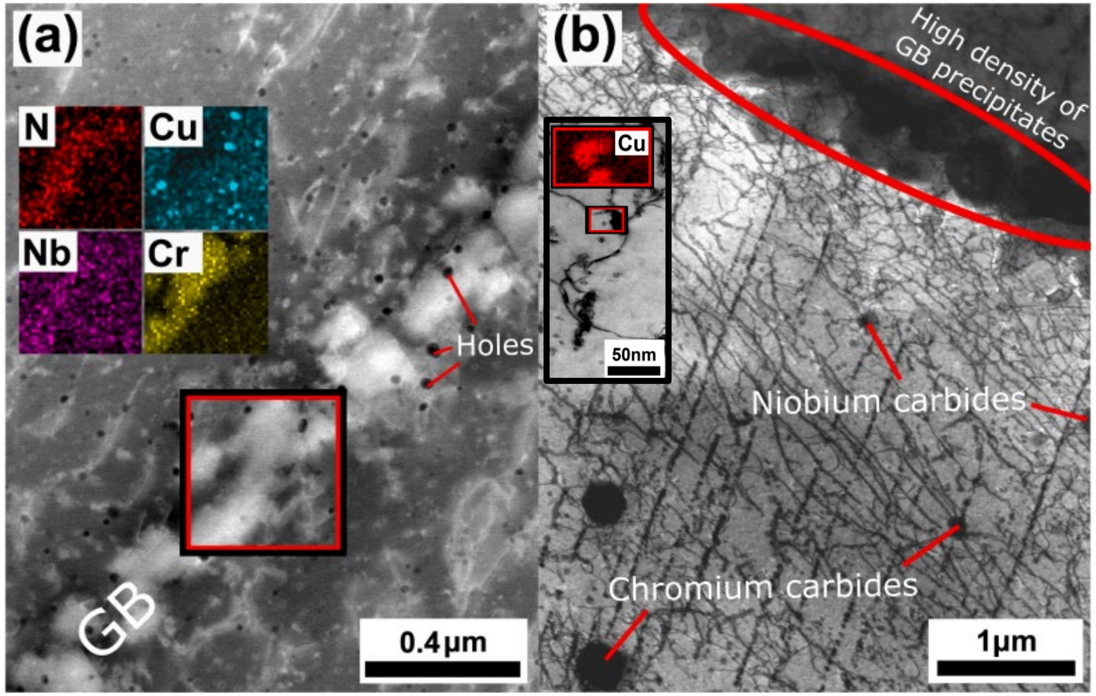


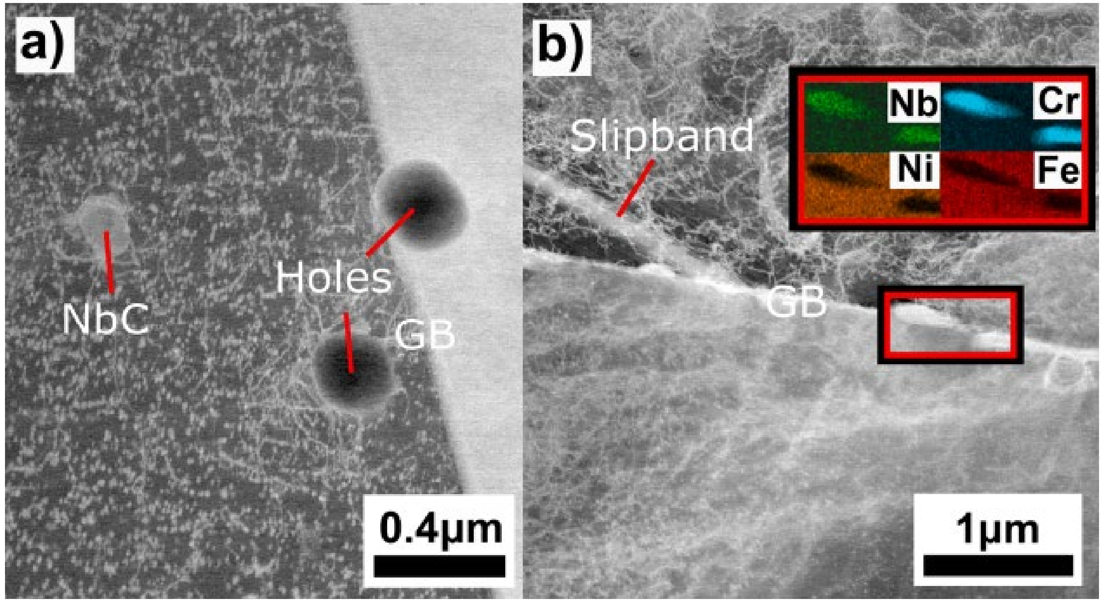
Image to the left: crack overview of Sanicro 25 (a) overview of the crack path, with EBSD and recrystallized fraction analysis of a zoomed in area of a highly plasticised zone containing a crack tip, (b) at the end of the crack path. Image to the right: schematic overview of the crack propagation and interaction process between creep and fatigue of Sanicro 25.

Precipitation – selected results

Sanicro 25 after testing (~200 h @ 700 °C)

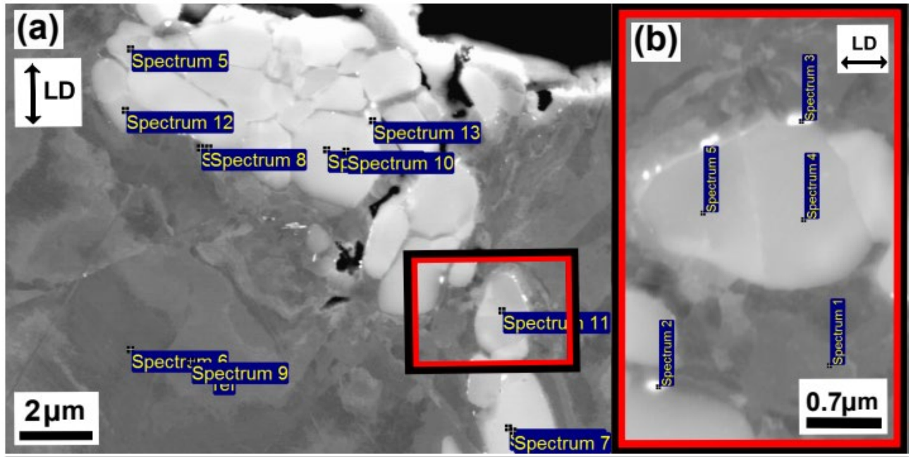


Esshete 1250 after testing (~150 h @ 700 °C)



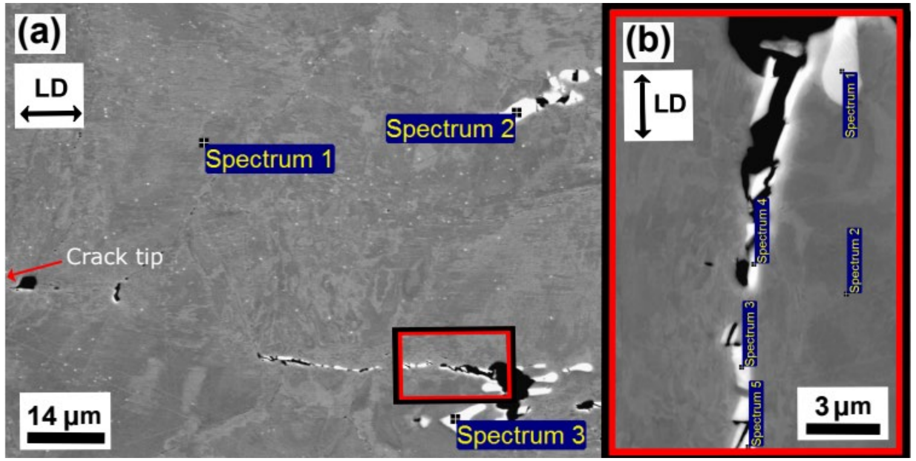
Micrographs of virgin Sanicro 25 and Esshete 1250 after fatigue and creep testing at 700 °C (a) STEM dark field imaging and (b) STEM bright field imaging. EDS-analysis of grain boundary precipitates in (a) or (b).

Sanicro 25 aged (3 000 h @ 650 °C)



Spectrums	C	Cr	N	Ni	Cu	Nb	W
a							
Spectrum 5	6.7	25.7	4.2	5.2	0.7	44.5	3.6
Spectrum 6/9 (ref)	3.3	22.2	0.5	24.0	2.8	0.4	3.6
Spectrum 7	5.9	27.0	3.7	0.6	0.2	57.5	4.3
Spectrum 8	6.7	24.0	0.9	14.1	7.5	16.9	4.7
Spectrum 10	6.9	26.9	4.4	1.1	0.2	56.3	3.8
Spectrum 11	6.0	27.9	5.6	2.2	0.3	52.5	3.5
Spectrum 12	5.3	23.3	1.5	12.3	1.4	29.0	4.0
Spectrum 13	7.2	25.3	2.4	4.3	0.6	47.8	4.6
b (enlarged image)							
Spectrum 1 (ref)	4.7	20.6	0.4	23.3	3.5	0.7	3.2
Spectrum 2	5.9	20.1	2.5	14.3	1.3	22.9	7.9
Spectrum 3	7.7	24.1	2.1	10.0	1.3	31.6	5.0
Spectrum 4	9.8	25.7	5.2	2.5	0.3	50.0	4.0
Spectrum 5	10	27.9	4.9	2.9	0.4	46.9	2.9

Esshete 1250 aged (3 000 h @ 650 °C)



Spectrums	C	Cr	Mn	Fe	Ni	Nb	Mo
a							
Spectrum 1 (ref)	2.9	15.4	7.2	61.0	9.8	0.9	1.4
Spectrum 2	16.4	4.1	1.6	12.9	1.6	62.7	0.1
Spectrum 3	6.7	11.1	4.6	43.6	6.1	26.3	0.9
b (enlarged image)							
Spectrum 1	18.3	1.4	0.5	3.3	0.41	75.1	0.3
Spectrum 2 (ref)	2.8	15.3	6.7	63.5	9.2	0.5	1
Spectrum 3	5.56	17.0	5.5	47.9	6.9	14.7	1.7
Spectrum 4	4.21	13.2	6.1	58.8	8.3	7.5	0.9
Spectrum 4	4.5	13.1	5.9	55.8	8.0	10.8	0.9

Micrograph of aged (3 000 h @ 650 °C) Sanicro 25 and Esshete 1250 (a) BSE image which show the EDS point spectrum positions and (b) enlarged BSE image which show the EDS point spectrum positions (zoomed image in (a). The quantitative EDS spectrum results (in wt.%) of the aged microstructure in the figure above.

Feasibility study – short summary

In this study one currently used boiler designs where final header material is P92 was compared to Sanicro 25.

- It was shown that a benefit offered by Sanicro25 is the high strength that allows a thinner wall thickness to be used.

Publication list from KME-801

Journal papers

1. H. Wärner, G. Chai, J. Moverare, M. Calmunger. High temperature fatigue of aged heavy section austenitic stainless steels, Materials, 2022, (15), 84.
2. H. Wärner, J. Xu, G. Chai, J. Moverare, M. Calmunger. Microstructural evolution during high temperature dwell-fatigue of austenitic stainless steels, International Journal of Fatigue, 2021, (143), 105990.
3. H. Wärner, M. Calmunger G. Chai, S. Johansson, J. Moverare. Thermomechanical fatigue behaviour of aged heat resistant austenitic alloys, International Journal of Fatigue, 2019, (127), pp. 509-521.

Conference papers

1. M. Calmunger, H. Wärner, G. Chai, M. Segersäll. Thermomechanical Fatigue of Heat Resistant Austenitic Alloys, Structural Integrity Procedia, 2023, (43), pp. 130-135.
2. H. Wärner, R. Eriksson, G. Chai, J. Moverare S. Johansson, M. Calmunger. Influence of ageing on thermomechanical fatigue of austenitic stainless steels, Procedia Structural Integrity, 2019, (23), pp. 354-359.
3. M. Calmunger, H. Wärner, G. Chai, S. Johansson, J. Moverare. High temperature properties of austenitic stainless steels for future power plant applications, EUROMAT 2019, 2019.
4. H. Wärner, M. Calmunger, G. Chai, S. Johansson, J. Moverare. Structural integrity and impact toughness of austenitic stainless steels, 13th International Conference on the Mechanical Behaviour of Materials (ICM13), 2019.
5. H. Wärner, M. Calmunger, G. Chai, J. Polák, R. Petráš, M. Heczko, T. Kruml, S. Johansson, J. Moverare. Fracture and Damage Behavior in an Advanced Heat Resistant Austenitic Stainless Steel During LCF, TMF and CF, Structural Integrity Procedia, 2018, (13), pp. 843-848.

Academic Theses

1. H. Wärner. High Temperature Fatigue Behaviour of Austenitic Stainless Steel - Microstructural Evolution during Dwell-Fatigue and Thermomechanical Fatigue, 2021, PhD Thesis, ISBN 978-91-7929-666-7.

Summary

This project has resulted in new knowledge and understanding of the two candidate austenitic stainless steels mechanical and microstructural evolution during TMF, fatigue and creep as well as the precipitation process.

This new knowledge can be used as a base for material selection regarding the future use of these materials in heavy section components in biomass-fired power plants.

In addition, the new knowledge and understanding can be used for material development and to some extent lighter power plant design.

Thank you for your attention!

Final report at Energiforsk.se

https://energiforsk.se/program/kme/rapporter/heavy-section-austenitic-stainless-steel-for-headers-and-piping-in-high-efficient-biomass-fired-power-plants/