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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Acknowledgment

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Sumitomo SHI FW

KME
CONSORTIUM MATERIALS TECHNOLOGY
for development and demonstration of thermal energy processes

Swedish Energy Agency

Energiforsk

Project group

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- Hugo Wärner (Linköping University, formar PhD student)
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Outline

- Background
  - Project goals
  - Alloys
- Methods and results
  - Thermomechanical fatigue
- Summary and conclusions

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Background

- 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.

Gärdstadverken Linköping.
Photo Åke E. Lindman

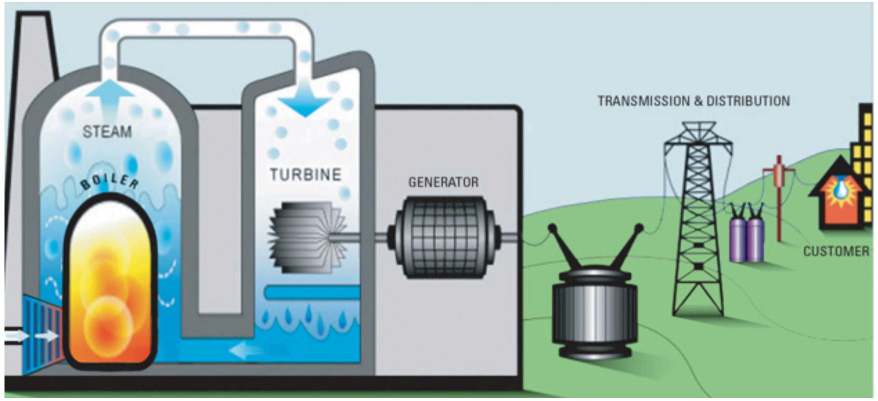


Image from Xcel Energy

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 (done).

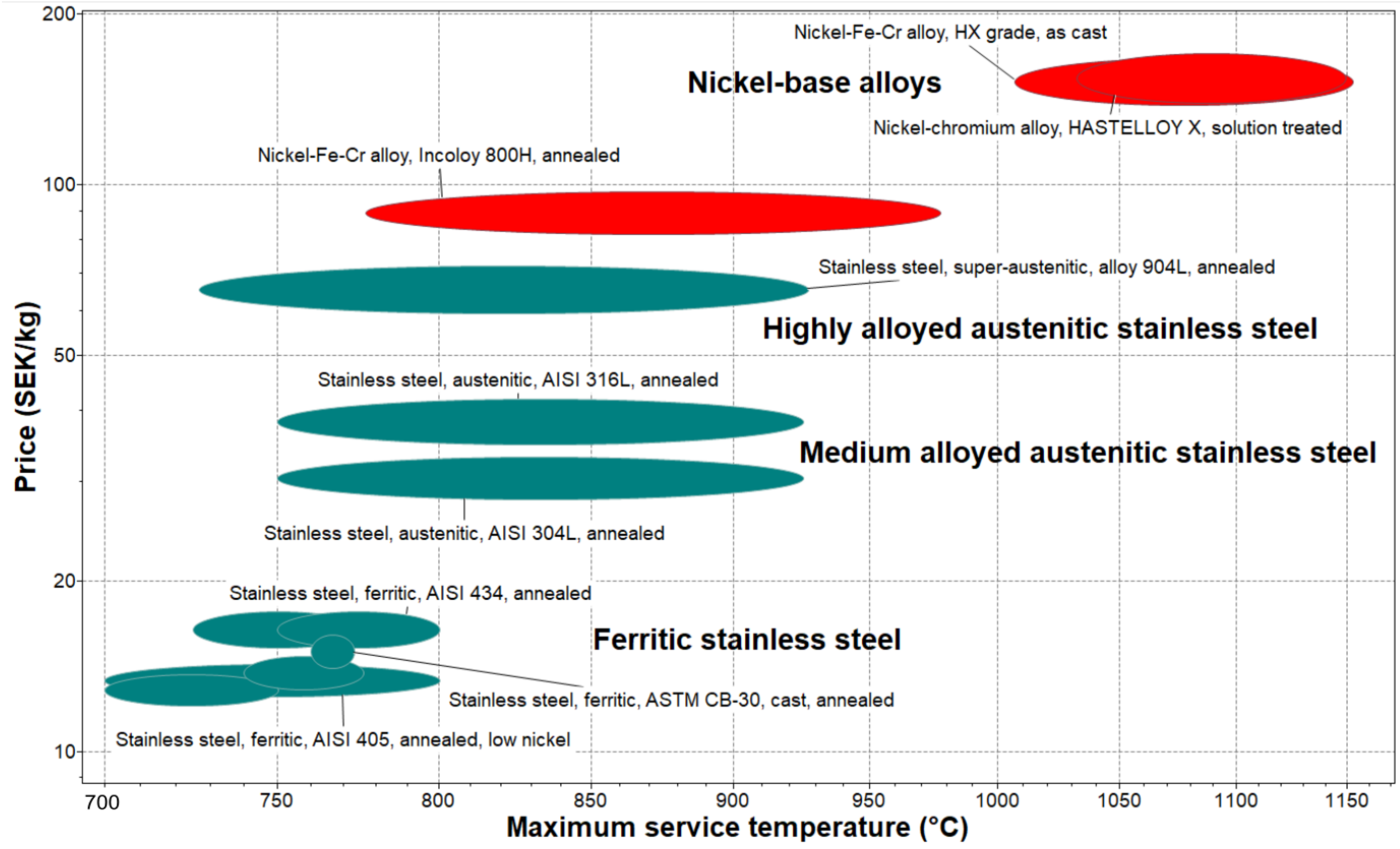
2) To **evaluate the fatigue crack propagation behavior** of new materials used in safety and reliability considerations since the material of critical components can undertake low cycle fatigue during the service (testing started).

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 (SSRT testing at LiU).

4) To **evaluate the structure stability and the toughness of welded and aged material** after long term service at high temperatures for safety analysis (testing will begin this autumn, welded material not available).

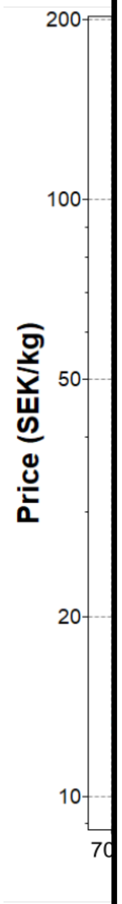
5) To **evaluate the new candidate material compared to currently used materials using FE-models** of the applications (preparing to start with TMF-testing of P91).

Alloys



Difference in price [SEK/kg] vs. Maximum service temperature [°C] for some power plant materials (From CES EduPack 2020).

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
	T/P122	Cr=12, W=2.0, Cu=1, Mn=0.6, Mo=0.4,V=0.2, Si=0.2, C=0.11, Nb=0.05, N=0.06, Fe=bal



Difference ... ls (From CES EduPack 2020).

Methods and results

- Thermomechanical fatigue testing

  - Results and analysis

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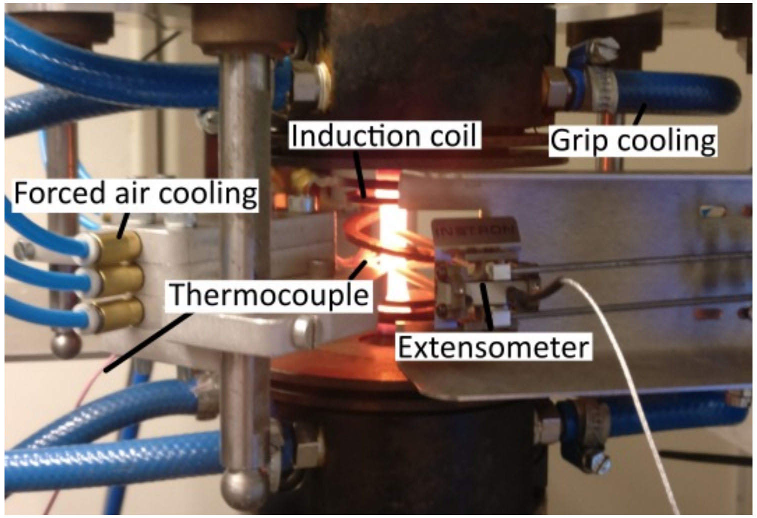
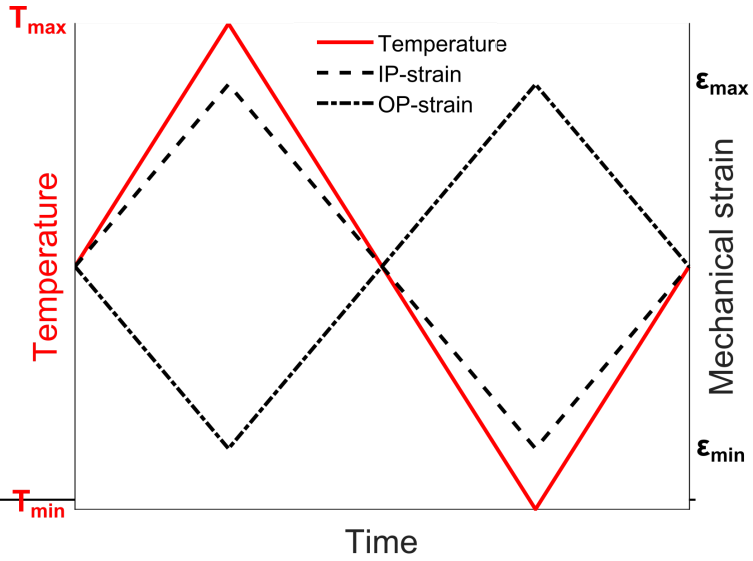
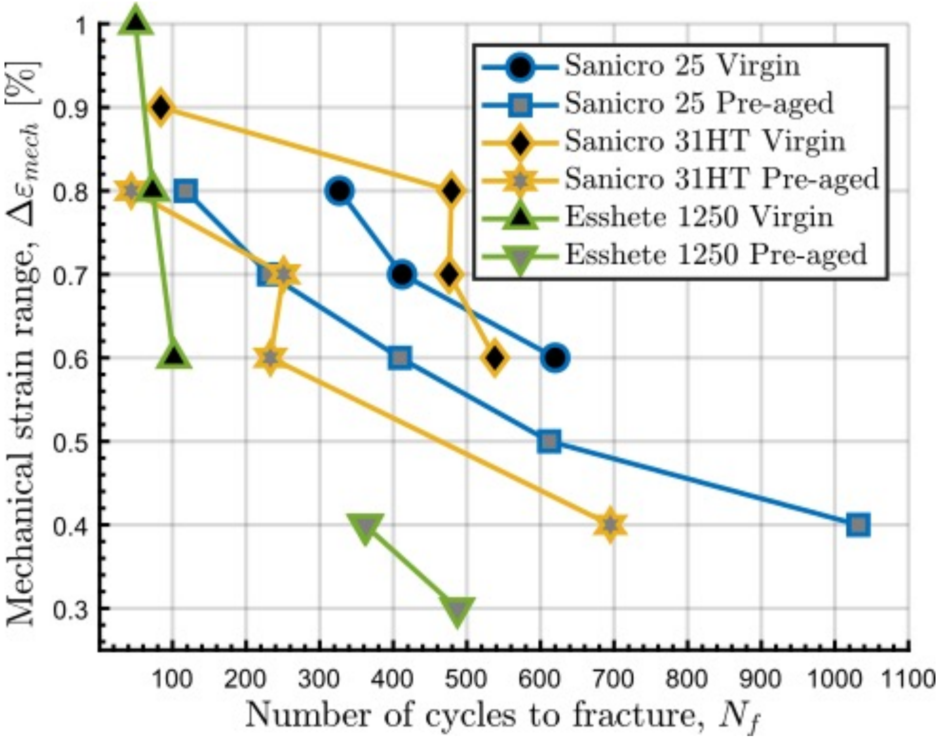
Thermomechanical fatigue testing (TMF)

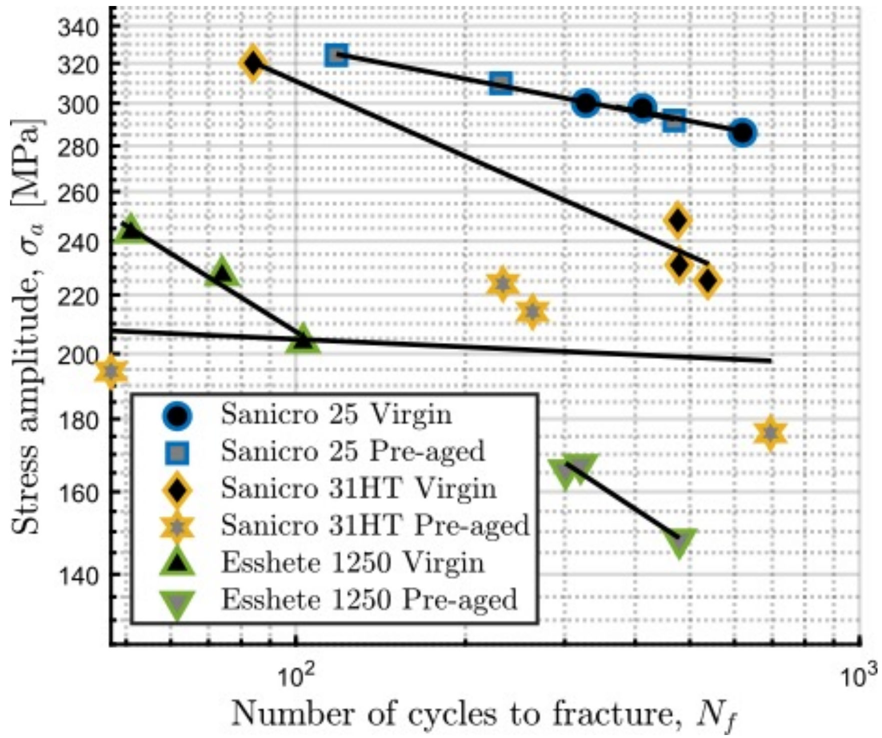
- Cycle type
  - Phase-shift: In-Phase (IP), Out-of-Phase (OP)
  - Heating/Cooling rate: 5°C/s
  - Maximum temperature: 600, **650**, 700, **800** °C
  - Minimum temperature: 100°C
- Instron 8801 servo hydraulic test machine
  - Strain controlled
- Ageing for 2000 (IP) and 3000h (OP) at maximum temperature



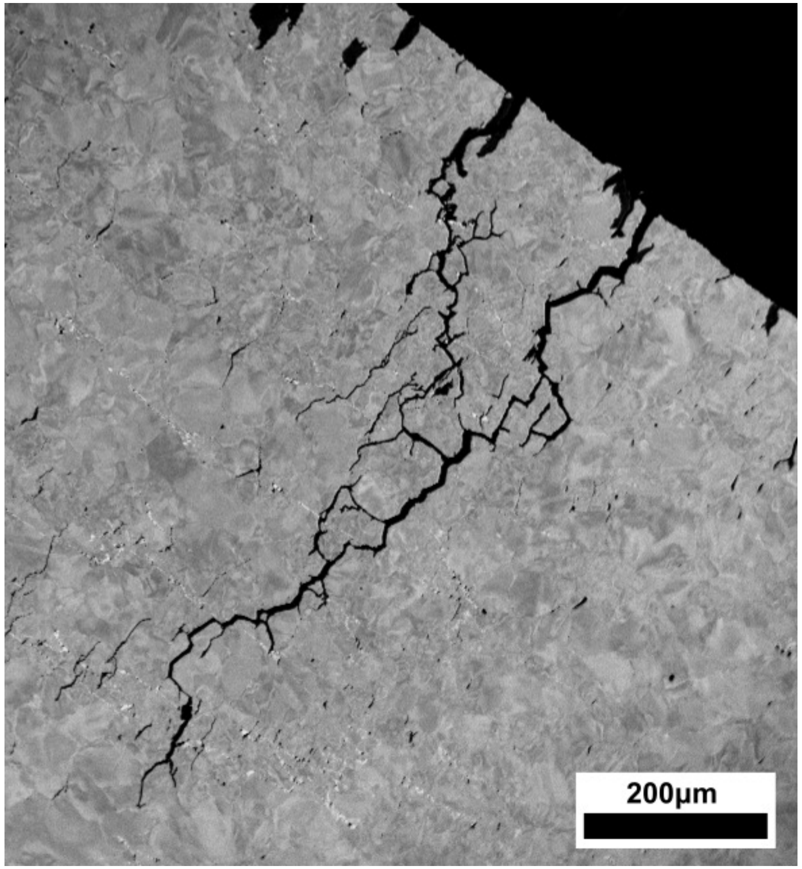


IP-TMF

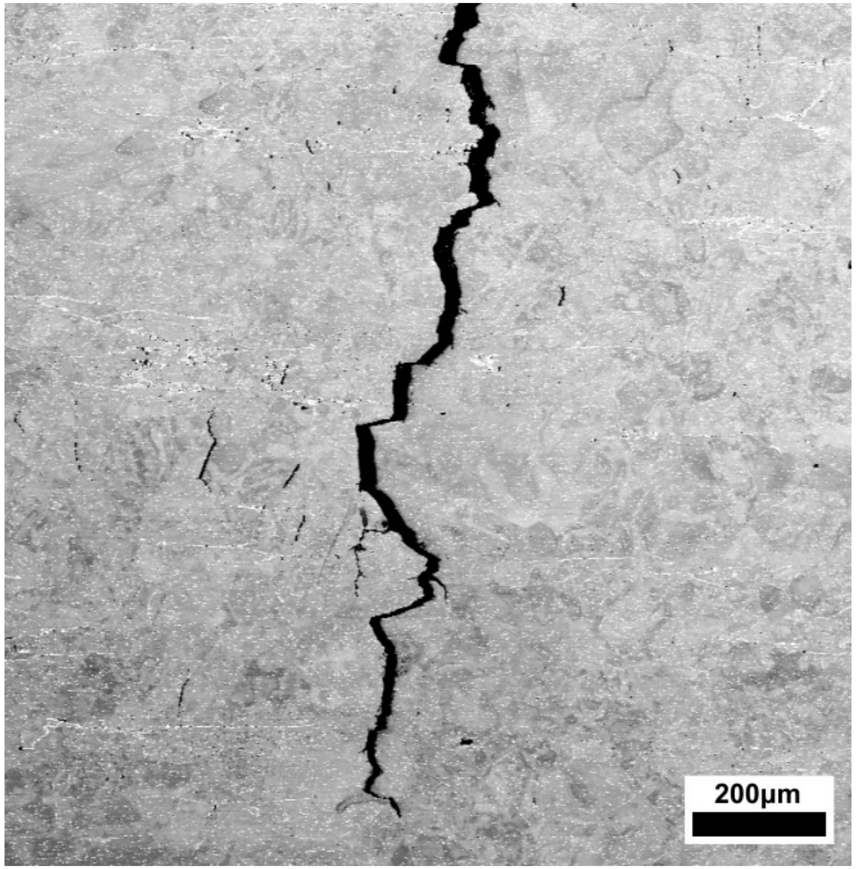

Mechanical strain range, $\Delta\varepsilon_{mech}$ [%]
Number of cycles to fracture, N_f
Sanicro 25 Virgin
Sanicro 25 Pre-aged
Sanicro 31HT Virgin
Sanicro 31HT Pre-aged
Esshete 1250 Virgin
Esshete 1250 Pre-aged


Stress amplitude, σ_a [MPa]
Number of cycles to fracture, N_f
Sanicro 25 Virgin
Sanicro 25 Pre-aged
Sanicro 31HT Virgin
Sanicro 31HT Pre-aged
Esshete 1250 Virgin
Esshete 1250 Pre-aged

IP-TMF: Failure mechanisms of Sanicro 25

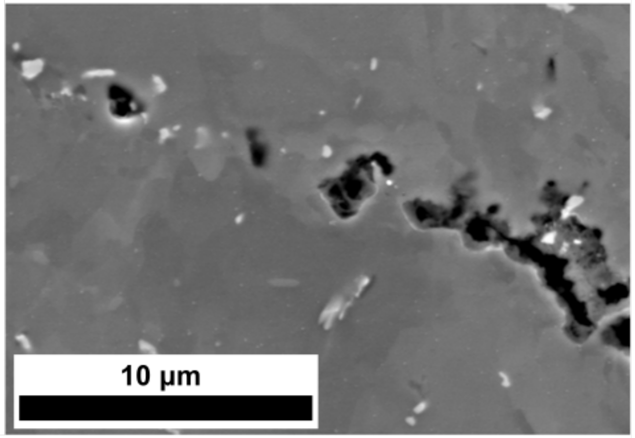


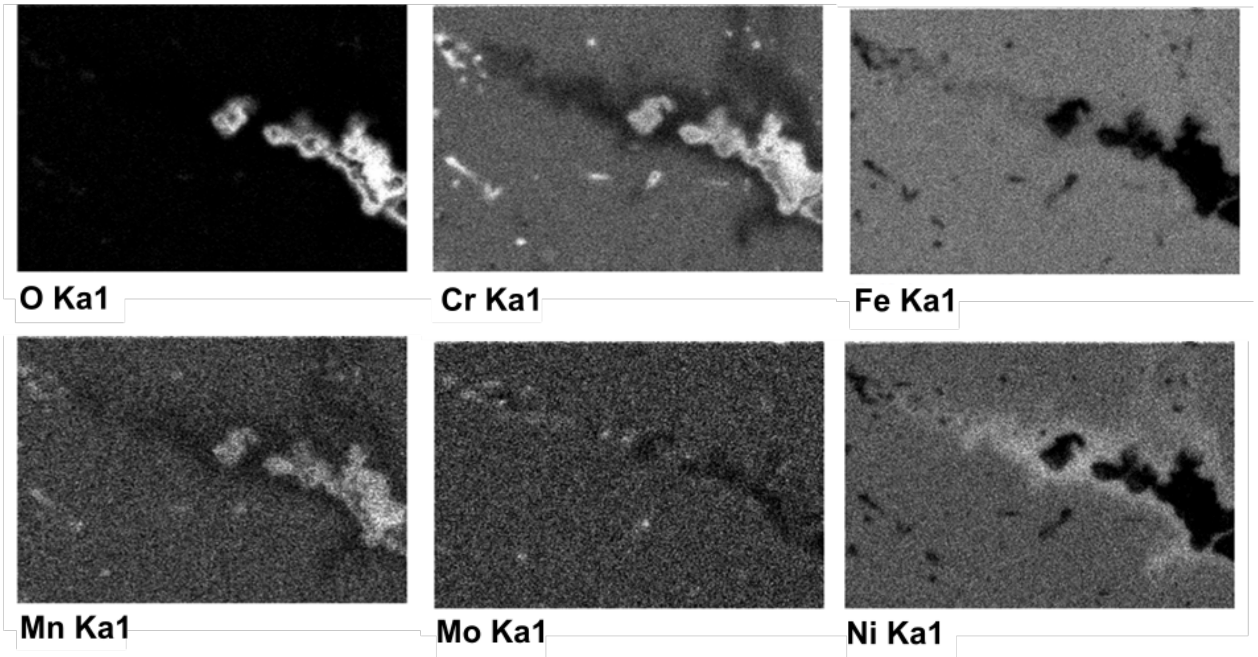
Micrograph of unaged Sanicro 25 with $\Delta\varepsilon_{mech} = 0.8\%$.
~400 cycles.



Micrograph of aged Sanicro 25 with $\Delta\varepsilon_{mech} = 0.6\%$.
~450 cycles.

IP-TMF: Failure mechanisms of Sanicro 25

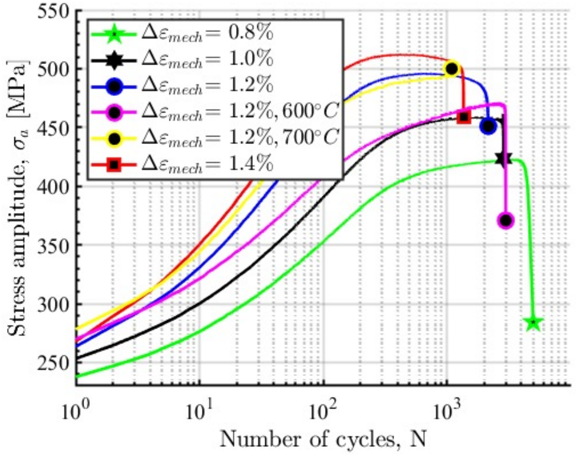




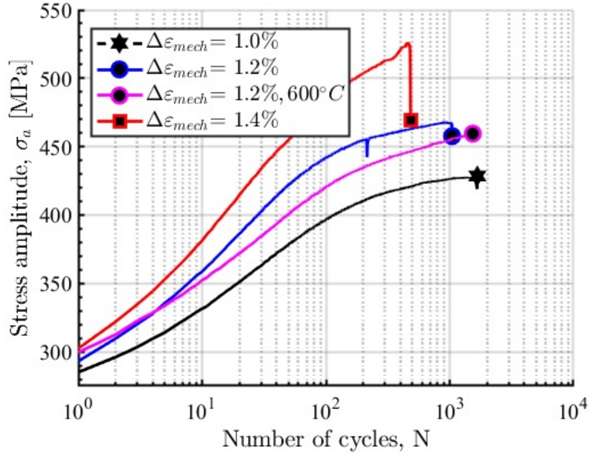
EDS analysis of aged Sanicro 25 with $\Delta\varepsilon_{mech} = 0.6\%$ ~450 cycles.

OP-TMF: Sanicro 25

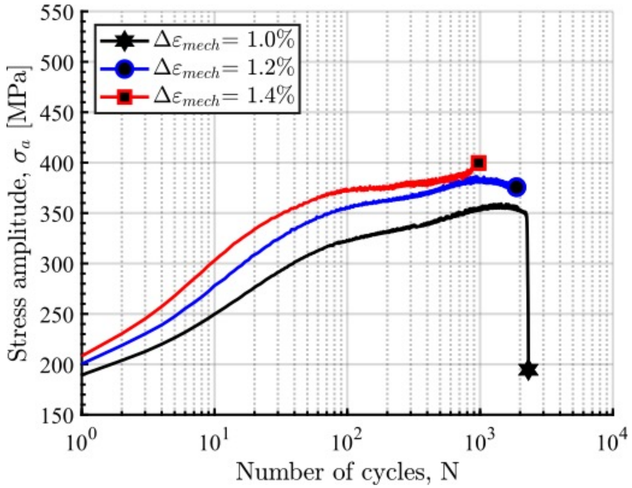
Unaged

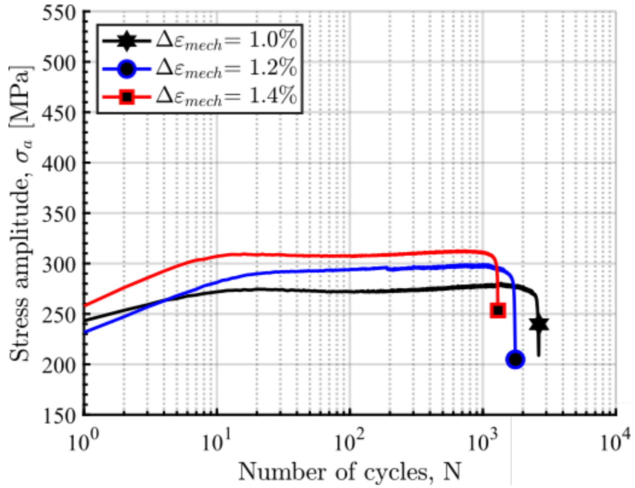


Aged 3000 h @ 650 °C

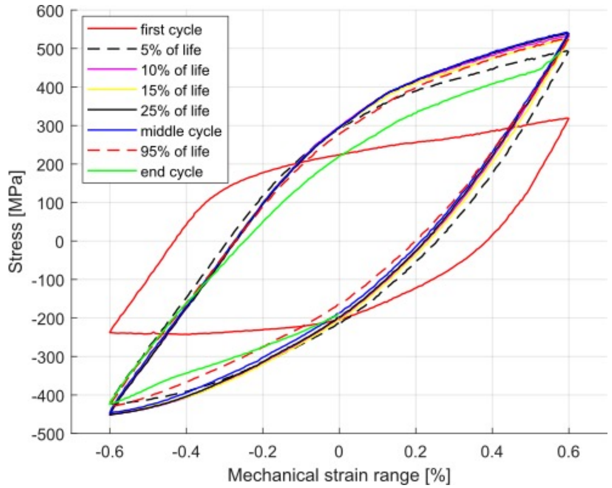


OP-TMF: Esshete 1250

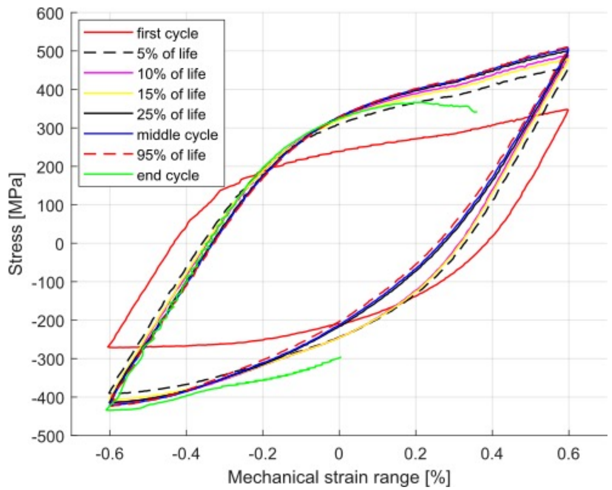


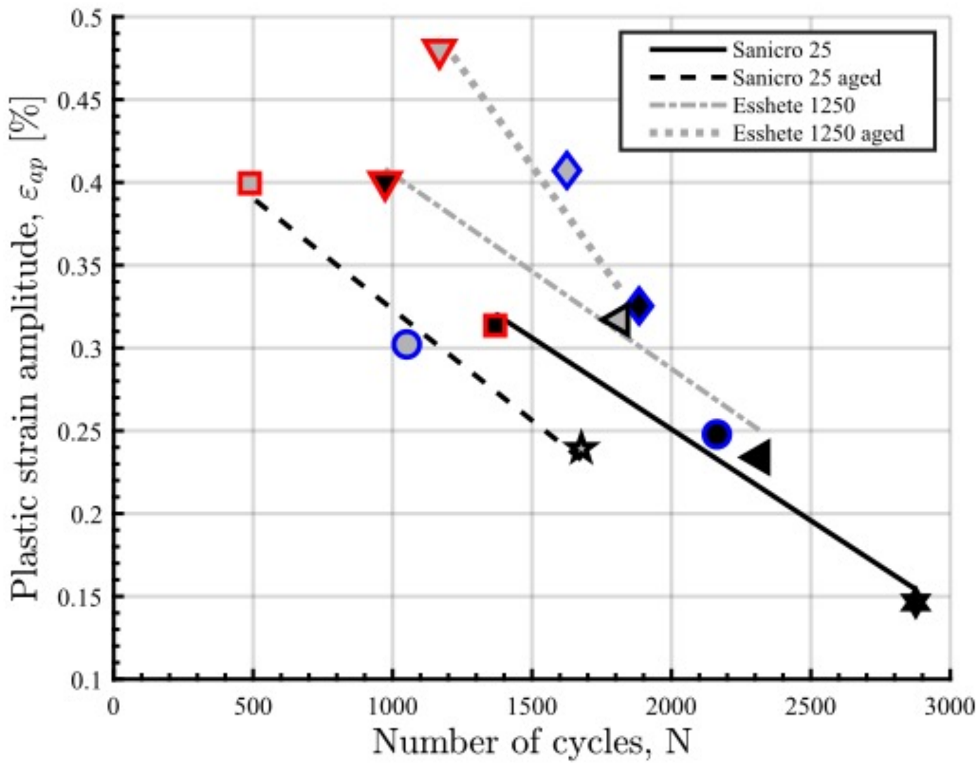


Sanicro 25 unaged

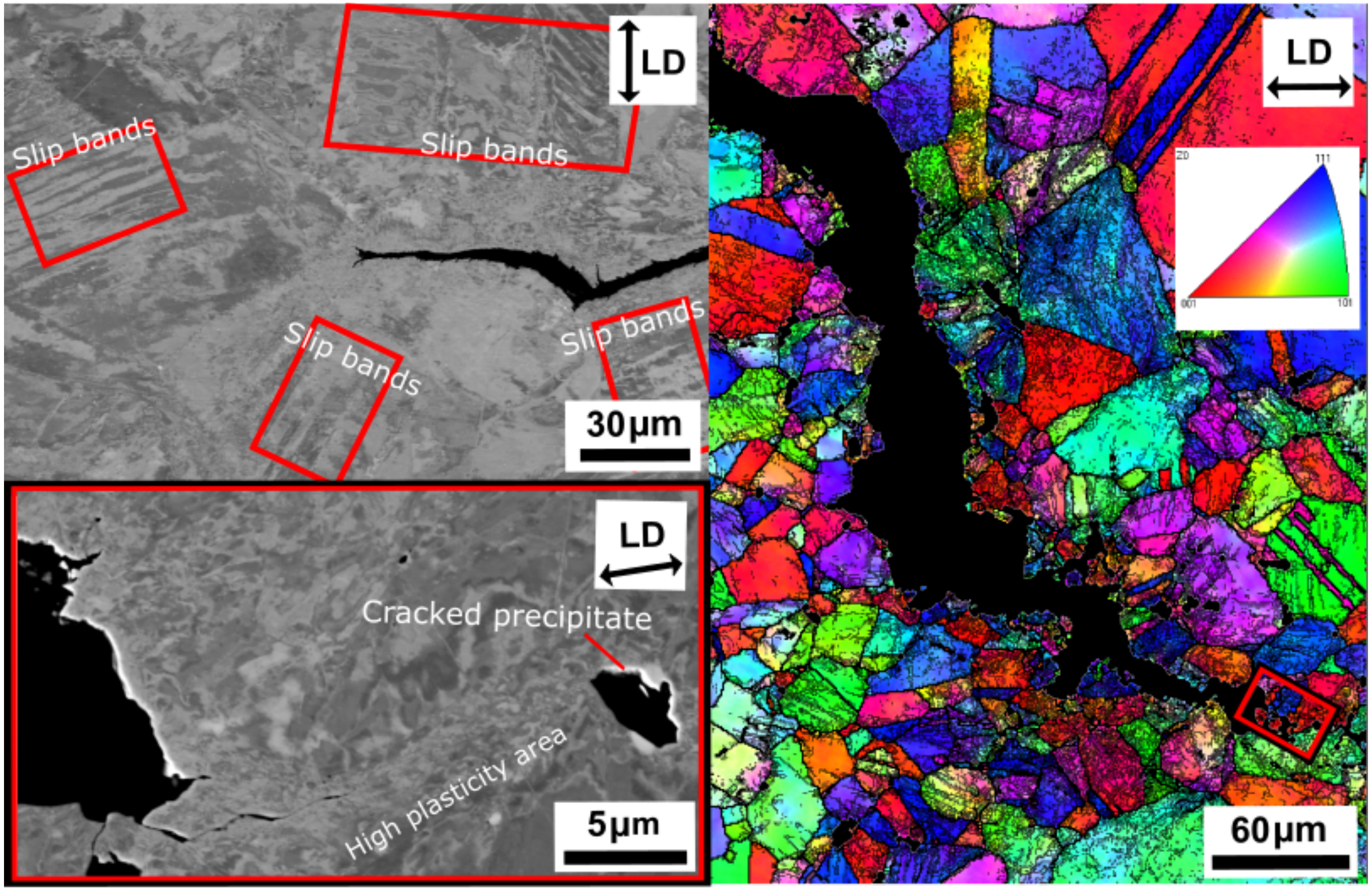


Sanicro 25 Aged 3000 h @ 650 °C



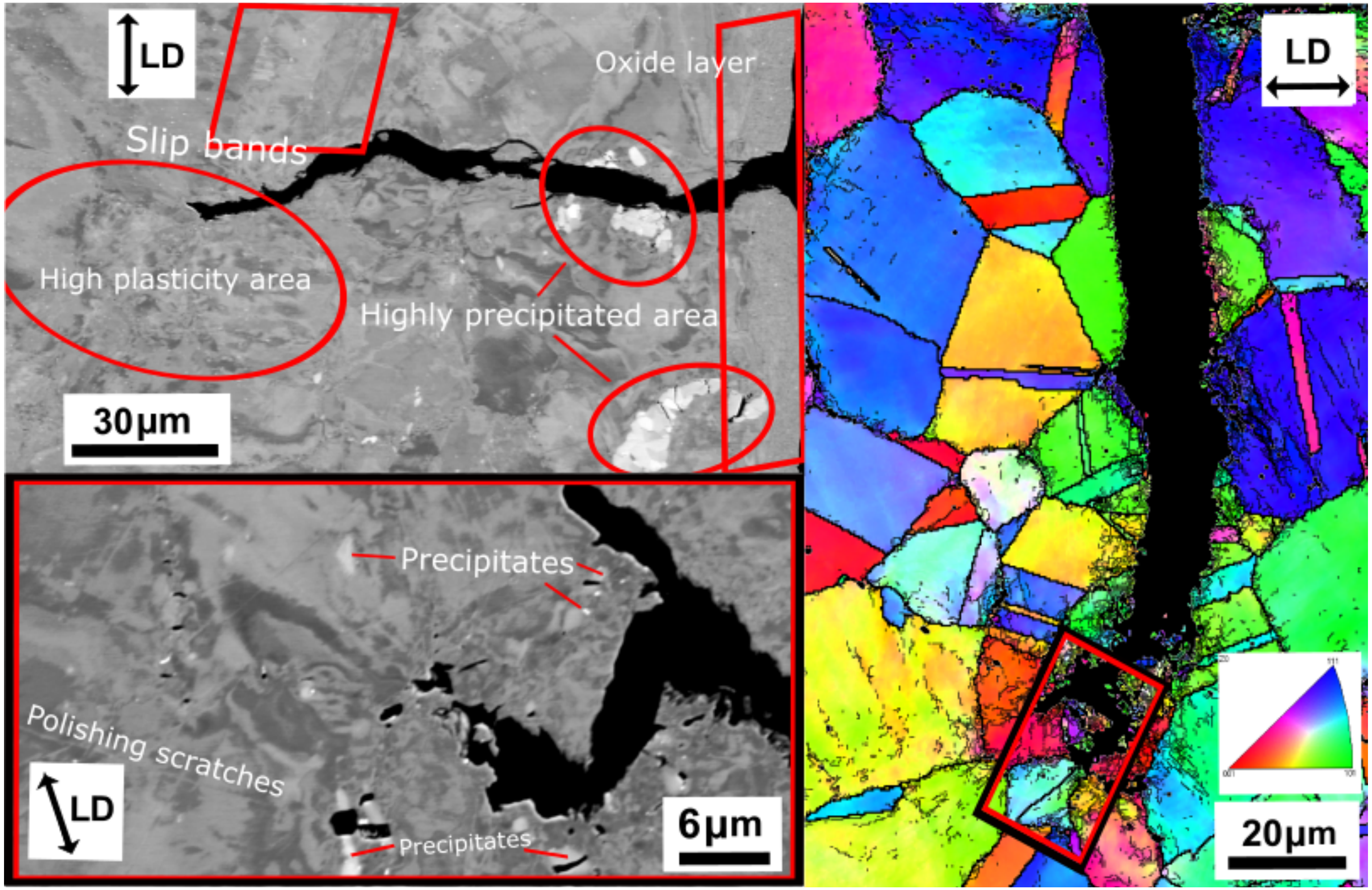


OP-TMF: Failure mechanisms of Sanicro 25



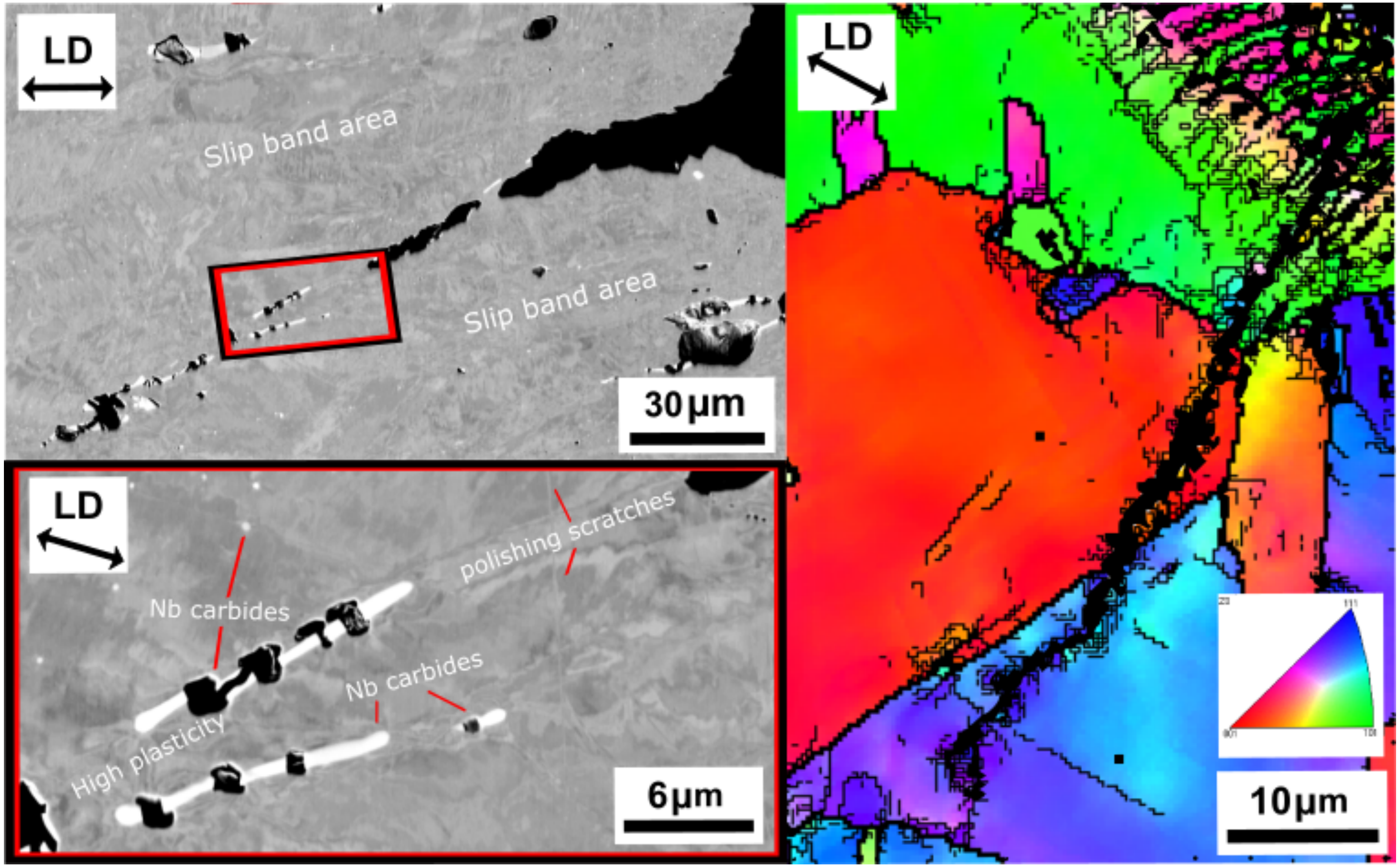
Micrograph of unaged Sanicro 25 with $\Delta\varepsilon_{mech} = 1.2\%$.
~2180 cycles.

OP-TMF: Failure mechanisms of Sanicro 25



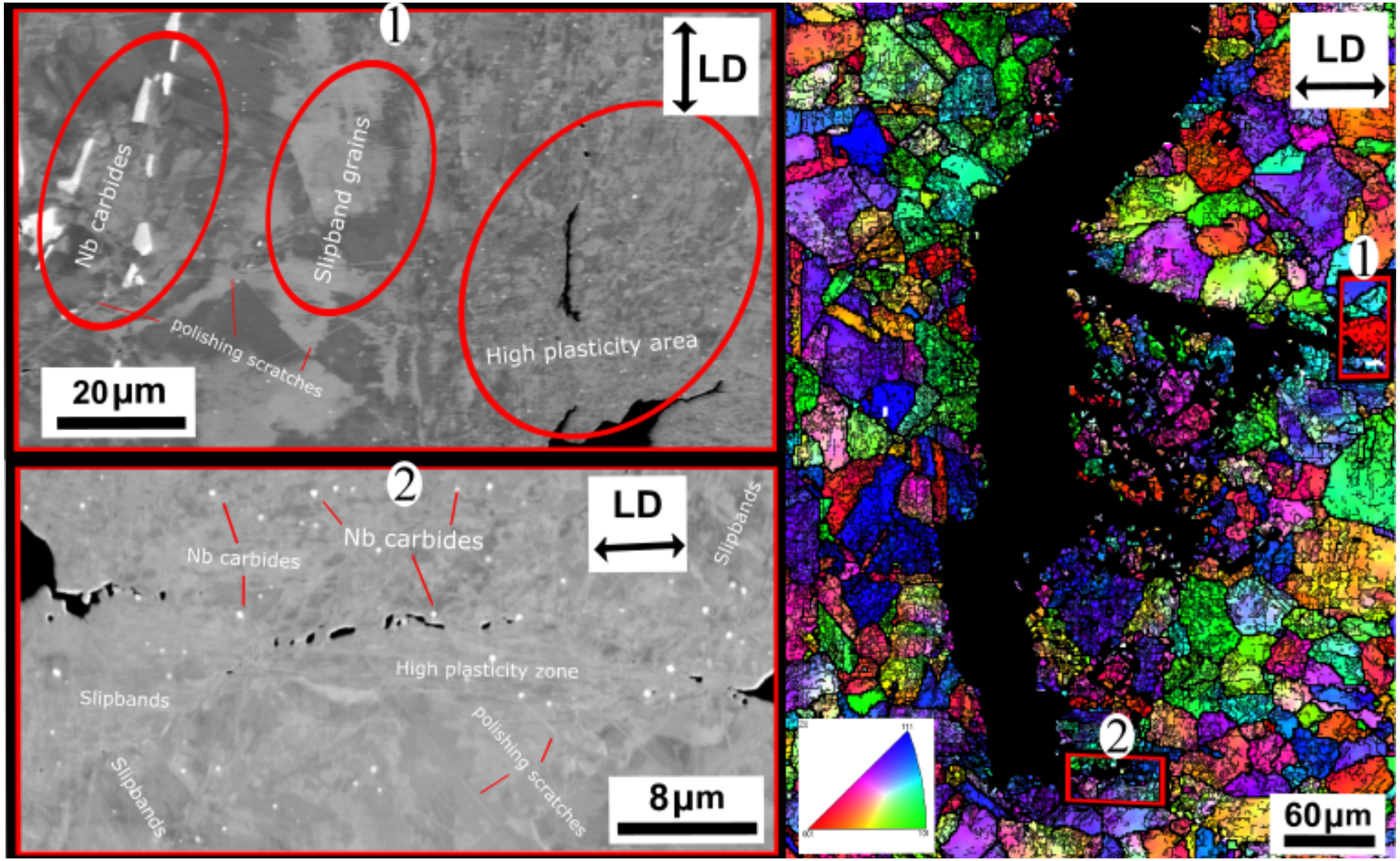
Micrograph of aged Sanicro 25 with $\Delta\varepsilon_{mech} = 1.2\%$.
~1050 cycles.

OP-TMF: Failure mechanisms of Esshete 1250



Micrograph of unaged Esshete1250 with $\Delta\varepsilon_{mech} = 1.2\%$.
~1800 cycles.

OP-TMF: Failure mechanisms of Esshete 1250



Micrograph of aged Esshete1250 with $\Delta\varepsilon_{mech} = 1.2\%$.
~1600 cycles.

Summary and conclusions

- Thermomechanical fatigue:
  - Detrimental effects from pre-ageing because of the deterioration of the microstructure, that enhanced creep, grain boundary embrittling and oxidation assisted cracking.
  - Cracking along the grain boundaries leading to fast fracture for the in-phase (IP) condition and transgranular propagating cracks for the out-of-phase (OP) condition.
  - OP-TMF crack propagation was assisted by slip band formation, cracking or decohesion of brittle precipitates and crack initiations from the oxidised surface, while the IP-TMF propagation was enhance by the embrittlement of the grain boundaries due to precipitation and oxidation assisted cracking.
- Future power plant boiler materials should possess high resistance to damage originating from high temperature plastic straining, creep and oxidation.

Thank you for your attention!

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Publication list KME 501, 701, 801

1. Deformation behaviour in advanced heat resistant materials during slow strain rate testing at elevated temperature
Theoretical and Applied Mechanics Letters, 2014, 4(041004), .

2. Mechanical Behaviours of Alloy 617 with Varied Strain Rate at High Temperatures
Materials Science Forum, 2014, 783-786, 1182-1187.

3. Influence of deformation rate on mechanical response of an AISI 316L austenitic stainless steel
Advanced Materials Research, 2014, 922, 49-54.

4. Long Term High-Temperature Environmental Effect on Impact Toughness in Austenitic Alloys
Key Engineering Materials, 2015, 627, 205-208.

5. Damage and Fracture Behaviours in Aged Austentic Materials During High-Temperature Slow Strain Rate Testing
Key Engineering Materials, 2014, 592-593, 590-593.

6. Advanced Microstructure Studies of an Austenitic Material Using EBSD in Elevated Temperature In-Situ Tensile Testing in SEM
Key Engineering Materials, 2014, 592-593, 497-500.

7. 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.

8. 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.

9. Influence of Dynamic Strain Ageing on Damage in Austenitic Stainless Steels
19th European Conference on Fracture (ECF19), August 26-31 2012, Kazan, Russia, 2012.

Cont. Publication list

10. Surface Phase Transformation in Austenitic Stainless Steel Induced by Cyclic Oxidation in Humidified Air
Corrosion Science, 2015, 100, 524-534.

11. Creep and Fatigue Interaction Behavior in Sanicro 25 Heat Resistant Austenitic Stainless Steel
Transactions of the Indian Institute of Metals, 2016, 69, 337-342.

12. Local surface phase stability during cyclic oxidation process
Materials Science Forum, 2017, 879, 855-860

13. Influence of dynamic strain ageing and long term ageing on deformation and fracture behaviors of Alloy 617
Materials Science Forum, 2017, 879, 306-311

14. Toughening Behavior in Alloy 617 with Long Term Ageing
Solid State Phenomena, 2017, 258, 302-305

15. Creep-fatigue interaction in heat resistant austenitic alloys
MATEC Web of Conferences 2018, 165, 05001

16. Fracture and Damage Behavior in an Advanced Heat Resistant Austenitic Stainless Steel During LCF, TMF and CF
Procedia Structural Integrity, Volume 13, 2018, Pages 843-848

17. Thermomechanical Fatigue Behaviour of Aged Heat Resistant Austenitic Alloys
International Journal of Fatigue, nr 127, 2019, s. 509-521

18. Structural Integrity and Impact Toughness of Austenitic Stainless Steels
Proceedings of the 13th International Conference on the Mechanical Behaviour of Materials 2019, s. 270-275

Cont. Publication list

19. Influence of Ageing on Thermomechanical Fatigue of Austenitic Stainless Steels
Procedia Structural Integrity, Elsevier, 2019, Vol. 23, s. 354-359

20. Microstructural Evolution During High Temperature Dwell-fatigue of Austenitic Stainless Steels
International Journal of Fatigue Vol. 143, 2021 artikel-id 105990

In addition, two Master thesis *Thermal mechanical fatigue behaviour of aged heat resistant austenitic alloys* (Wärner, 2016) and *The Influence of Dynamic Strain Aging on Austenitic Stainless Steels* (Calmunger, 2011), two Licentiate thesis *High-Temperature Behaviour of Austenitic Alloys* (Calmunger, 2013) and *High-Temperature Fatigue Behaviour of Austenitic Stainless Steel: Influence of Ageing on Thermomechanical Fatigue and Creep-Fatigue Interaction* (Wärner 2018) and two PhD theses *On High-Temperature Behaviours of Heat Resistant Austenitic Alloys* (Calmunger, 2015) and *High Temperature Fatigue Behaviour of Austenitic Stainless Steel: Microstructural Evolution during Dwell-Fatigue and Thermomechanical Fatigue* (Wärner, 2021) have been produced within KME 501, 701 and 801.