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Thermomechanical Fatigue of Heat Resistant Austenitic Alloys

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Abstract

Rising global energy consumption and the increase in emissions of greenhouse gases (e.g. CO_2) causing global warming, make need for more sustainable power generation. This could be accomplished by increasing the efficiency of the biomass-fired power plants, which is achieved by increasing the temperature and pressure. In addition, flexible generation of power is critical if only renewable power generation is to be achieved and this will increase the number of start-and stop cycles. Cyclic condition in a long-term high temperature environment is an operation process that such materials must withstand, in order to satisfy the needs for future power generation.

Commonly austenitic stainless steel are used for critical components of power plants. Because of future change in operating conditions, further investigations are needed to verify that the demands on safety for cyclic long-term usage is fulfilled. This work includes investigation of two commercial austenitic steels: Esshete 1250 and Sanicro 25. The materials were exposed to thermomechanical fatigue (TMF) in strain control under In-Phase and Out-of-Phase conditions and main testing temperature ranges of 100-650°C and 100-800 °C respectively. Some of the specimens were pre-aged to simulate prolonged service condition. Mechanical test data were obtained and analysed in order to define the TMF performance of the investigated alloys. The differences in performance were discussed in relation to mechanical and microstructural characterization.

Keywords: Austenitic stainless steel; In-Phase and Out-of-Phase Thermomechanical fatigue; Pre-ageing; Microstructural characterization.

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1. Introduction

The increase in global energy consumption and the emissions of greenhouse gases (e.g. CO2) causing global warming, require a need for more sustainable power generation (World Energy Council (2013)). This could be accomplished by increasing the efficiency of biomass-fired power plants, which can be achieved by increasing the temperature and pressure in the boiler sections (Yin (2009)). In addition, a flexible generation of power is critical if only renewable power generation is to be achieved, which will increase the number of start and stop cycles (Dietrich (2013)). The change in operating conditions will increase the demands on the materials in the critical components of the biomass-fired power plants. Cyclic operating condition in a long-term high temperature environment is a process that such materials must withstand, in order to satisfy the needs in future power generation. Since the lifetime of power plants is expected to be 30 years or more, the materials used for critical components need to have good long-term high temperature performance in order to maintain structural integrity and fulfil safety requirements (Viklund (2013); Sourmail (2001)).

Commonly, austenitic stainless steel is used for the critical components of power plants in for instance super heaters (Yin (2009)) but might also be a possible candidate for heavy section components exposed to high temperature (Wärner (2022)). Because of future changes in operating conditions, more investigations are needed to verify that the demands on safety and structural integrity for long-term use are fulfilled. One way to investigate the simultaneous change in both mechanical load and temperature of the materials used in new efficient biomass-fired power plants is to study their thermomechanical fatigue (TMF) behaviour. In-Phase (IP) TMF (tensile loading is concurrent with heating and maximum tensile strain coincides with maximum temperature) give a good estimation of the boiler component behaviour during start up and shut down operating condition in a power plant (Wärner (2019); Polák (2020); Wärner (2022)). TMF testing in an Out-of-Phase (OP) condition (compressive loading is concurrent with heating and maximum tensile strain coincides with minimum temperature) shows a similar temperature and mechanical profile that simulates the real component condition for a hot-spot surrounded by colder material or the hot-side of a thicker wall with a temperature gradient (Petráš (2021); Wärner (2022)).

This study includes investigation of two commercial austenitic steels: Esshete 1250 and Sanicro 25. The materials were exposed to TMF in strain control under IP and OP condition with main testing temperature ranges of 100-800 °C and 100-650°C respectively. Some of the material were pre-aged before testing up to 3000 hours at up to 800 °C. Mechanical test data were obtained and analysed in order to define the TMF life of the investigated austenitic alloys. The differences in performance were discussed in relation to mechanical and microstructural characterization.

2. Experimental procedures

2.1 Materials

The investigation involved two commercial austenitic alloys: Sanicro 25 (solution heat-treated at 1220 °C for 10 min) and Esshete 1250 (solution heat-treated at 1100 °C for 15 min). Sandvik Materials Technology AB have provided and heat-treated the materials. The chemical compositions of the investigated materials in wt.% are given in Table 1. Some of the specimens were pre-aged at 650 for 3 000 and 10 000 hours and at 800 °C for 2000 hours.

Table 1: Chemical composition (in wt.%) of the austenitic alloys, with Fe as balance (Bal.) element.

Alloy	C	Cr	Ni	W	Co	Cu	Mn	Nb	N	Si	V	Mo	Fe
Sanicro 25	0.1	22.5	25	3.6	1.5	3.0	0.5	0.5	0.23	0.2	-	-	Bal.
Esshete 1250	0.1	15	9.5	-	-	-	6.3	1.0	-	0.5	0.3	1.0	Bal.

2.2 Mechanical characterization

The testing procedure employed was strain controlled TMF testing. The test machine was a servo-hydraulic TMF machine from Instron with induction heating and forced air-cooling. Before the TMF tests the machine was carefully aligned, to prevent buckling and other instability effects, according to “the validated code of practice” (Hähner (2006)). This study includes the IP-TMF cycle with $R_{\varepsilon mech}$=0 and OP-TMF cycle with $R_{\varepsilon mech}$=-1. For the IP tests, a 5 min dwell time at maximum mechanical strain range and maximum temperature was used. The temperature range for IP-TMF was 100-800 °C and for OP-TMF 100-650 °C (main), 100-600 °C and 100-700 °C (reference) were used, the temperature range differ between IP and OP condition due to different industrial conditions, all temperature ranges had a heating and cooling rate of 5 °C/s. For the IP-TMF an cylindrical specimen with a diameter of 6.35 mm and a parallel length of 24.58 mm and for the OP-TMF an cylindrical specimen with a diameter of 8.0 mm and a parallel length of 20.0 mm, more details can be found in Wärner (2019) and Wärner (2022) respectively. The setup of the tests were done according to Hähner (2006), with spot welded thermocouples aligned in the longitudinal direction, at a distance of 1mm between each other and the strain was measured with a high-temperature extensometer with a gauge length of 12.5 mm. The thermal strain was subtracted from the measured total strain, so that the mechanical strain could be controlled (Hähner (2006)). The number of cycles to failure was defined as the point where the maximum stress range decreases 10% (Hähner (2006)). However, the test was not stopped until a load drop of 60% occurred.

2.3 Microstructural characterization

After testing, the specimens were cut using electric discharge machining along the longitudinal cross sections of the tested specimens and were ground and polished following the procedure used in Wärner (2019). The microstructural investigations were performed with a HITACHI SU-70 field emission gun (FEG)-SEM equipped with a solid-state backscattered electron (BSE) detector, using 10 kV acc. voltage and working distances ranging 7-15 mm.

3. Results and discussion

3.1 Mechanical response

In Fig. 1 the difference in cyclic hardening and softening for the IP-TMF cycled virgin and pre-aged Sanicro 25 and Esshete 1250 can be seen. The pre-aged Esshete 1250 material could not be tested at higher strain range than 0.4 % without fracture after insufficient number of cycles. Sanicro 25 shows a stronger cyclic hardening, higher stress levels and longer IP-TMF life compared to Esshete 1250 during IP-TMF. Both alloys shows a decrease in IP-TMF life from pre-ageing when comparing virgin (Fig.1 a) and c)) and pre-aged (Fig.1 b) and d)) materials.

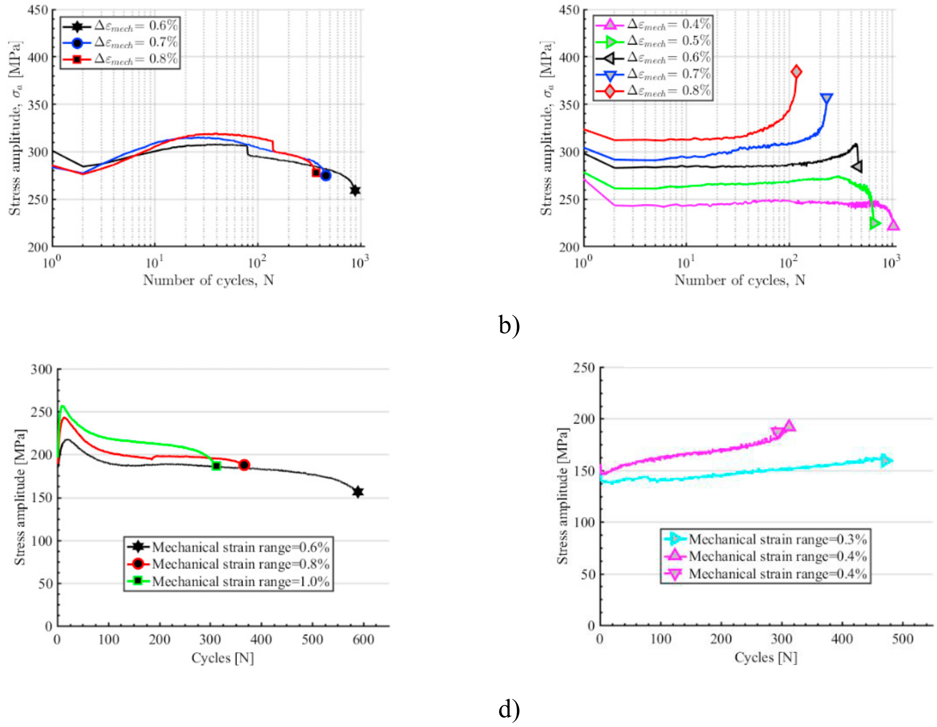

Figure 1: IP-TMF stress amplitude vs cycles curves for Sanicro 25 a) virgin and b) aged (2000 h at 800 °C) and Esshete 1250 virgin and b) aged (2000 h at 800 °C). Data are also published in Wärner (2019).

The OP-TMF cyclic hardening and softening curves of Sanicro 25 and Esshete 1250 in virgin and aged condition are displayed in Fig. 2. Also in OP-TMF, Sanicro 25 shows a stronger cyclic hardening, higher stress level and longer OP-TMF life comparing virgin condition (Fig.2 a) and d)) with Esshete 1250. However, Esshete 1250 shows similar

OP-TMF life after pre-ageing as the virgin material but with reduced strength. The OP-TMF life of Sanicro 25 decreases after pre-ageing but with less reduced strength compared to Esshete 1250. Actually, Sanicro 25 has higher strength after 10 000 hours of ageing at 650 °C compared to virgin Esshete 1250.

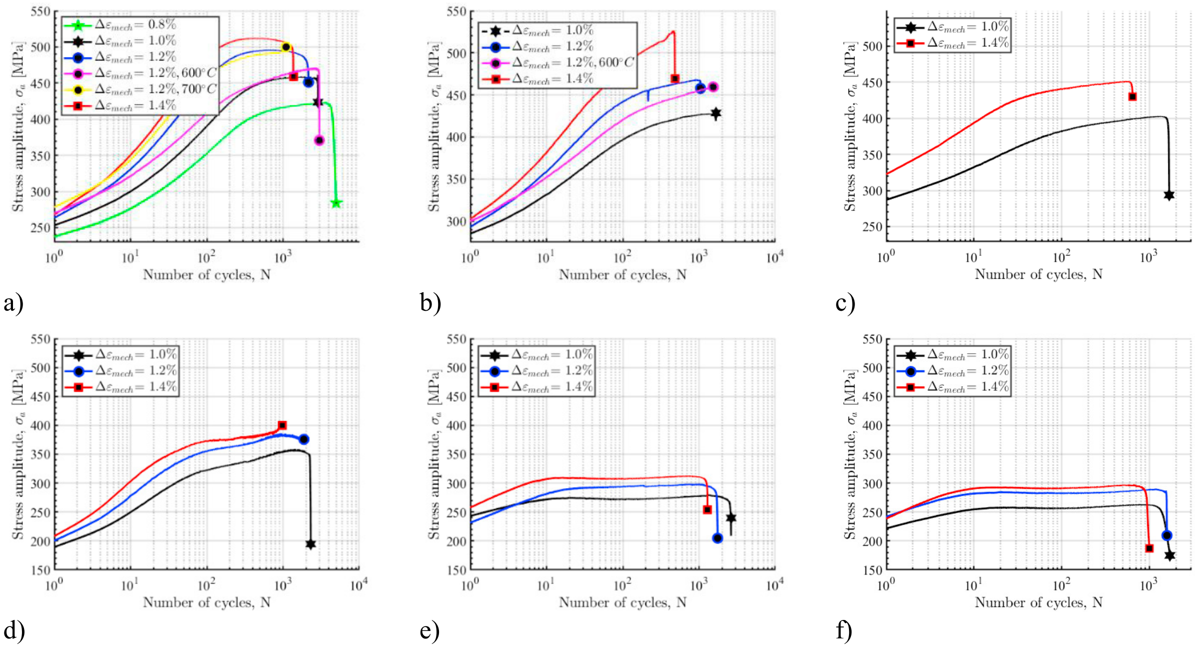

Figure 2: OP-TMF stress amplitude vs cycles curves for Sanicro 25 a) virgin, b) aged (3000 h at 650 °C) and c) aged (10 000 h at 650 °C) and Esshete 1250 d) virgin, d) aged (3000 h at 650 °C) and f) aged (10 000 h at 650 °C). Data (a), b), d), e)) are also published in Wärner (2022).

Considering both IP- and OP-TMF results, Sanicro 25 shows better TMF performance compared to Esshete 1250 in both virgin and pre-aged condition. Since Sanicro 25 compared to Esshete 1250, show superior IP-TMF performance in both virgin and pre-aged conditions and better OP-TMF performance in virgin condition, as well as preserved strength even though the number of cycles are reduced for the pre-aged samples tested with OP-TMF. However, both alloys show detrimental effects from pre-ageing, since either TMF life and/or strength were reduced when the samples were pre-aged.

3.2 Microstructural evolution

The microstructures of TMF tested Sanicro 25 under different conditions are displayed in Fig. 3. In Wärner (2019) and Wärner (2022) the precipitates in virgin Sanicro 25 after TMF testing were identified as Nb(C, N), Z-phase, μ-phase and $M_{23}C_6$. After pre-ageing and TMF testing Sanicro 25 show Z-phase, Laves-phase and $M_{23}C_6$ according to Wärner (2019) and Wärner (2022). The cyclic hardening and high strength at elevated temperature of Sanicro 25, have been attributed to the presence of coherent Cu-rich nanoparticles homogeneously precipitated throughout the matrix (Heczko (2017)). Findings of tungsten and strain induced NbC precipitates in solid solution together with the Cu-rich nanoparticles in combination with high dislocation density were reported to greatly contribute to the obstruction of dislocation movement (Heczko (2017); Polák (2020); Petráš (2021)). The reduced TMF life of the aged specimens correlates to the reduced ability for impeding of dislocation movement and the reduced solid solution strengthening by the loss of solute atoms as a consequence of the precipitation process. The microstructural evolution during ageing and TMF are accelerated compared to the virgin condition and promotes the decrease and coarsening of the strengthening precipitates, as well as formation of new detrimental or not as effective precipitates. For all conditions, the crack initiations are facilitated by cracking of the surface oxide layer (Polák (2020); Petráš (2021)). All tested TMF conditions show mainly intergranular cracking (Fig. 3 & 4). The OP-TMF tested specimens also show high deformation in the interior of the grains (Fig. 3 & Fig. 4 c) & d)). The crack propagation of IP-TMF in both virgin and pre-aged condition were oxidation assisted (Fig. 3 & Fig. 4 a)). No clear evidence of oxidation assistant crack propagation was found in OP-TMF.

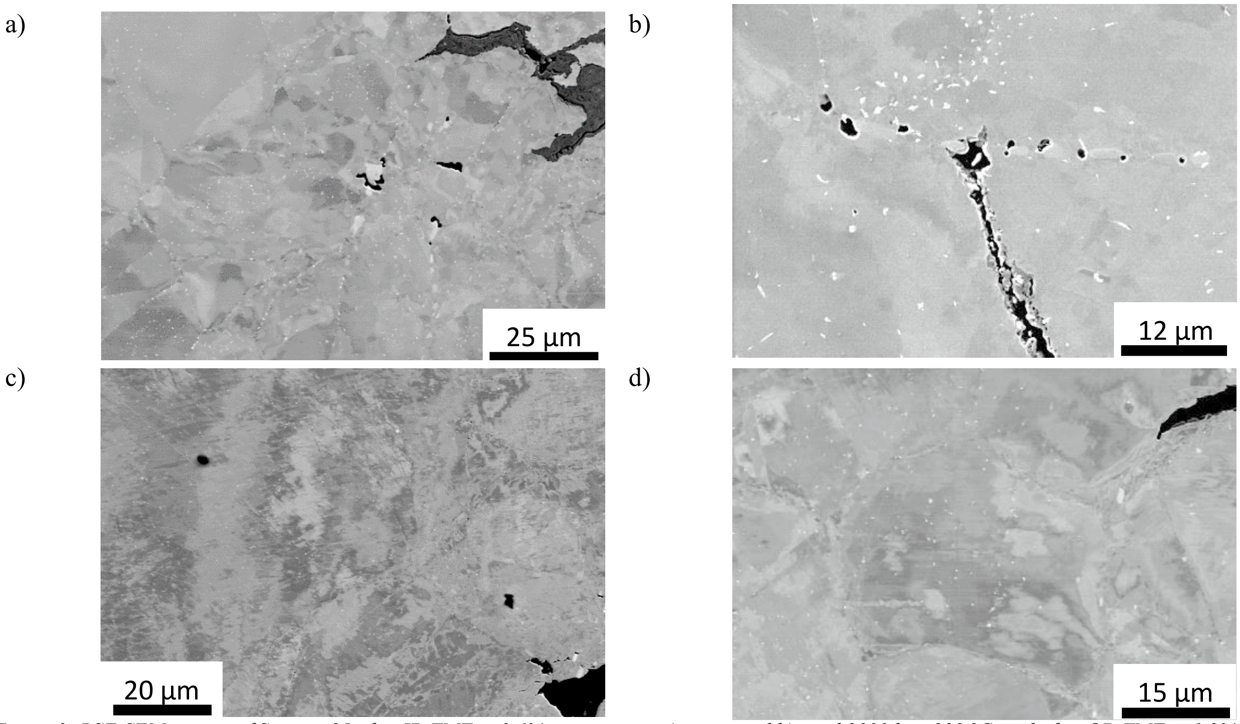

Figure 3: BSE-SEM images of Sanicro 25 after IP-TMF at 0.6% strain range a) virgin and b) aged 2000 h at 800 °C, and after OP-TMF at 1.2% strain range c) virgin and d) aged 3000 h at 650 °C.

In Fig. 4 the microstructure of TMF tested Esshete 1250 are shown. According to Wärner (2019) and Wärner (2022) the bright precipitates in virgin and pre-aged Esshete 1250 after TMF testing were identified as NbC by using energy dispersive spectroscopy in an SEM.

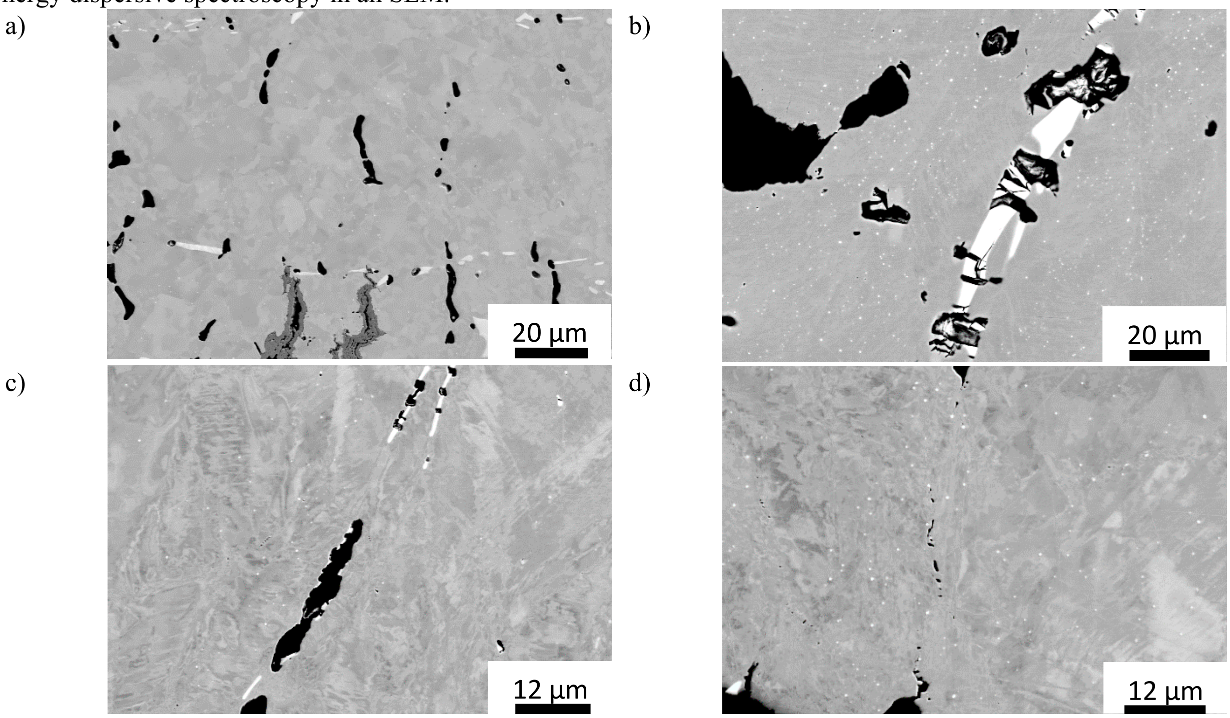

Figure 4: BSE-SEM images of Esshete 1250 after IP-TMF at 0.6% and 0.3% strain range respectively a) virgin and b) aged 2000 h at 800 °C, and after OP-TMF at 1.2% strain range c) virgin and d) aged 3000 h at 650 °C.

According to Fig. 4, the crack propagation seems to be associated with cracking of the NbCs. For the aged specimens (Fig. 4 b)), the NbCs were coarser and grouped together in certain areas and this should be the reason for the reduced strength. The virgin specimens suffered higher stresses when cycled to the predetermined strain level, locally a high enough stress level could be reached for cracking of the NbCs, which would assist the crack propagation (Fig. 4 c)).

4. Conclusions

The thermomechanical fatigue performance of two austenitic alloys were analysed. The influence of prolonged service degradation was simulated by pre-ageing of some specimens before TMF testing. The mechanical results were analysed and processed. SEM was used to investigate the microstructure after testing, in order to understand the mechanical behaviour of the alloys during TMF testing. From this study, these conclusions were reached:

- Both alloys experienced a detrimental effect on the TMF performance by the influence of pre-ageing. The reduction in TMF performance was attributed to an accelerated microstructural evolution that provided decreased effectiveness for impeding dislocation motion.
- Comparing TMF performance, Sanicro 25 showed compared to Esshete 1250 a better performance and higher strength for both IP and OP testing conditions including virgin and aged materials. This was attributed to the superior microstructural strengthening mechanisms during high temperature conditions.

Acknowledgements

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References

Dietrich K, Latorre JM, Olmos L, Ramos A., 2013. The role of flexible demands in smart energy systems. Energy Syst Springer, 79.

Heczko M, Esser BD, Smith TM, Beran P, Mazánová V, McComb DW, et al., 2018. Atomic resolution characterization of strengthening nanoparticles in a new high-temperature-capable 43Fe-25Ni-22.5Cr austenitic stainless steel. Mater Sci Eng A 719, 49.

Hähner P, Affeldt E, Beck T, Klingelhöffer H, Loveday M, Rinaldi C., 2006. Final version of the validated code-of-practice for thermo-mechanical fatigue testing. Tech. Rep., European Comission: Directorate-General Joint Research Centre.

Petráš R, Šulák I, Polák J, 2021. The effect of dwell on thermomechanical fatigue in superaustenitic steel Sanicro 25. Fatigue Fract Eng Mater Struct. 44, 673.

Polák J, Petráš R, 2020. Cyclic plastic response and damage mechanisms in superaustenitic steel Sanicro 25 in high temperature cycling – Effect of tensile dwells and thermomechanical cycling. Theoretical and Applied Fracture Mechanics 108, 102641.

Sourmail T., 2001. Precipitation in creep resistant austenitic stainless steels. Mater Sci Technol 17, 1.

Viklund P, Hjörnhede A, Henderson P, Stålenheim A, Pettersson R., 2013. Corrosion of superheater materials in a waste-to-energy plant. Fuel Process Technol 105, 106.

World Energy Council. World Energy Resources 2013, Tech. rep., World Energy Council, London; 2013.

Wärner, H., Calmunger M., Chai, G., Johansson, S., Moverare, J., 2019. Thermomechanical fatigue behaviour of aged heat resistant austenitic alloys. International Journal of Fatigue 127, 509.

Wärner, H.; Chai, G.; Moverare, J.; Calmunger, M., 2022. High Temperature Fatigue of Aged Heavy Section Austenitic Stainless Steels. Materials 15, 84.

Yin J, Wu Z., 2009. Corrosion behavior of TP316L of superheater in biomass boiler with simulated atmosphere and deposit. Chinese J Chem Eng 17, 849.