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Environmentally Assisted Fatigue of Cladding Weld Material

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ABSTRACT

Components of nuclear power plants (NPP), including those covered by cladding weld material as pressure vessel, typically experience fluctuating thermal stresses and pressure due to plant start-ups, shut-downs, and thermal transients during operation. Operational loading can lead to low cycle fatigue (LCF) damage in thicker sections of the components. Therefore, understanding the LCF behaviour of cladding weld materials is crucial for safe plant operation. ÚJV Řež, a. s. is dedicated to testing cladding weld materials used in WWER reactors and is particularly interested in enhancing confidence in its data by conducting tests at JRC on commonly used cladding weld materials for reactor pressure vessels (RPV) and other components in the primary circuit.

As part of the UJV-JRC inter-laboratory testing of cladding weld materials in a Water – Water Energetic Reactor environment (WWER), the project will experimentally examine the impact of primary coolant on the fatigue life of austenitic materials in a simulated WWER primary water environment through strain-controlled fatigue tests. The resulting data will facilitate inter-laboratory comparisons between UJV and JRC laboratories regarding the cladding weld metal as well.

The ENAFCLAD (Environmentally Assisted Fatigue of Cladding Weld Materials) project aims not only to broaden the database of low cycle fatigue test results for the austenitic cladding weld material Sv04Ch20N10G2B in the primary nuclear circuit of WWER 1000 but also to compare results from specimens of identical geometry and the same experimental material obtained from two testing devices: Pluto 6 (UJV Řež, a. s.) and Autoclave 1 (JRC Petten, EMMA – AMALIA laboratory). Consequently, the project will provide significant evidence to enhance the credibility and comparability of the conducted experiments and evaluated data.

This article summarizes the low-cycle fatigue test results of Sv04Ch20N10G2B specimens in an environment that simulates the primary water of WWER 1000 reactors, as part of the Open Access Joint Research Centre program of the European Commission.

INTRODUCTION

NPP are a key component of global energy production, ensuring stable electricity supplies with minimal greenhouse gas emissions. The safety and long-term reliability of their operation are therefore critical factors influencing their use. Primary circuit components, including RPVs, are exposed to demanding operating conditions, including cyclic mechanical loading, high temperature and the influence of coolant (RPV is not in contact with coolant). One of the key degradation mechanisms that can affect their service life is the LCF (low cycle fatigue) of cladding weld materials.
Environmentally assisted fatigue (EAF) is a specific type of material damage caused by repeated mechanical loading, which can lead to initiation and propagation of cracks in material. In primary circuit environment of a nuclear reactor, this process is further influenced by the presence of coolant containing chemicals that can accelerate material degradation through corrosion mechanisms. Another important factor is the operating temperature, which affects the kinetics of damage and the fatigue life limit.
In a nuclear reactor environment, a combination of mechanical stress and corrosive action of the coolant leads to EAF. This form of degradation can have a significant impact on the mechanical integrity of critical components and consequently on the overall safety of the plant. It is therefore essential to carry out detailed experimental studies aimed at understanding the behaviour of cladding weld materials under real operating conditions.
The ENAFCLAD (Environmentally Assisted Fatigue of Cladding Weld Materials) project focuses on experimental investigation of fatigue behaviour of the austenitic cladding weld material Sv04Ch20N10G2B, which is commonly used in WWER-1000 reactors. The aim is not only to extend the database of available low-cycle fatigue results for this material but also to compare data obtained in different laboratories using identical specimens and methodologies. An important aspect of this project is the cooperation between ÚJV Řež, a. s. and the JRC Petten laboratory within the framework of the European Commission's Joint Research Programme.

EXPERIMENTAL PROGRAM

MATERIAL

The austenitic cladding material Sv04Ch20N10G2B was used in the EAF experimental program as part of the ENAFCLAD project. Used cladding material employed in WWER nuclear reactors as a protective layer on the inner surface of the RPV and other primary circuit components. This material offers excellent resistance to corrosion, low-cycle fatigue (LCF), and thermal stress, which are crucial for ensuring the long-term safety and reliability of nuclear power plants.

EAF TESTING DEVICES

The Pluto 6 (ÚJV Řež, a. s.) autoclave is an experimental device developed for corrosion – mechanical testing. Pluto 6 is used for EAF testing in water or gas environments. Specimen is loaded by pressure differential above and below the bellows. Pressure above bellows is generated by a circulation pump in case of a watery environment and by a pressure cylinder in a gas environment. Pressure under bellows is generated hydraulically by a pressuring device. For testing in a water environment, device is connected to a flow – through water circuit that controls chemical parameters of the medium throughout autoclave. Basic technical parameters of the device:

- Pressure: 12,5 MPa,
- Max. temperature: 320°C,
- Max. flow rate: 2 litres/hour,
- Frequency of loading, only for EAF: < 0,05 Hz.

Autoclave 1 (EMMA AMALIA JRC Petten) is an experimental device for corrosion-mechanical tests. In this device, it is possible to perform EAF tests in air and water environments up to a medium temperature of 360 °C. A pneumatic system – bellows – is used for the axial loading of the test specimens. The load on the test body is generated using the pressure change in the bellows. If the pressure in the bellows is higher than the pressure of the medium in the autoclave, the specimen is loaded into pressure. If, on the other hand, the pressure in the bellows is lower than the pressure in the autoclave, the specimen is loaded in tension. The maximum load generated is ± 17 kN, which corresponds to a stress of ± 601 MPa for the test specimens with a circular cross-section of 6 mm in diameter. The design of both experimental devices Pluto6 (ÚJV Řež, a. s.) and Autoclave 1 (EMMA AMALIA JRC) is shown in Figure 1.

Figure 1. The design of experimental devices Pluto 6 (left) and Autoclave 1 (right)

The design of the specimen geometry used for EAF tests during the ENAFCLAD project for autoclave Pluto 6 and Autoclave 1 is shown on Figure 1 (ÚJV Řež, a. s. design).

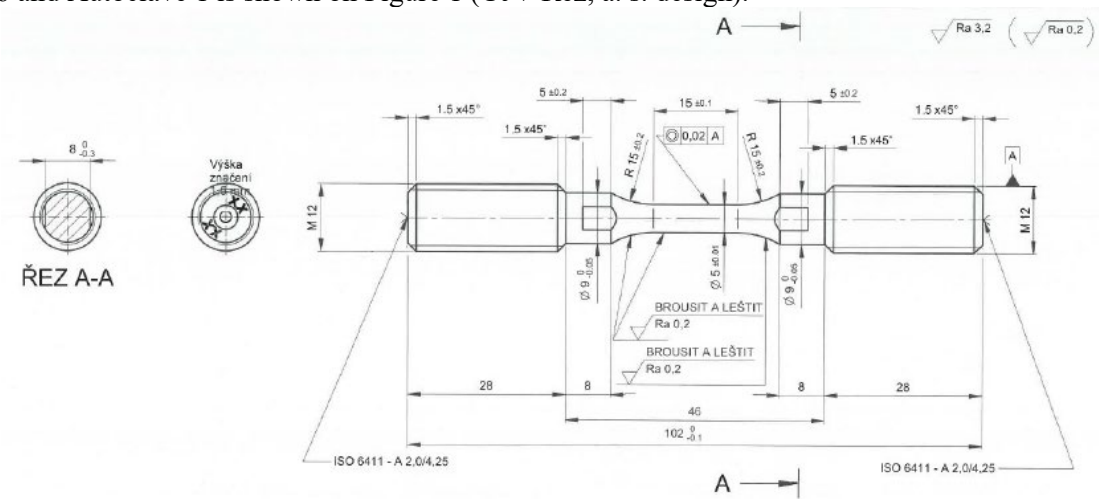

Figure 2. Specimen geometry used for EAF test during the ENAFCLAD project

TEST ENVIRONMENT

All tests were performed in a water environment simulating the primary circuit coolant of the WWER-1000 reactor type. Required environmental parameters are given in Table 1.

Table 1: Nominal composition of test environment (wt.%)

Substance/property	Nominal composition
H_3BO_3	0,087 ± 0,001
KOH	(1,46 ±0,01) x 10^{-3}
NH_3	0,00124
O_2	<5 x 10^{-7}
H_2	3 x 10^{-4}
Cl^-	<5 x 10^{-6}
SO_4^{2-}	<5 x 10^{-6}
Conductivity	80 – 100 µS/cm
pH	6,8 – 7,6

Before loading, during and at the end of all tests in water environment, grab samples were taken at intel and analysed. Special fluoroplastic sample containers designed for trace analysis were used. During test, sample were taken three days after start of loading, i.e. one sample every two weeks.
The samples were analysed for boron, lithium or potassium, fluorine and chlorine using an optical cuvettes test with detection limits around 100 ppb. Sulphur was determined by ICP-MS (Inductively Coupled Plasma Mass Spectrometry) with detection limit of 50 ppb.
Oxygen was measured on-line during test at outlet of autoclave. Hydrogen was calculated at intel from Henry's law using overpressure and ambient temperature. Only pH at 25°C was measured at inlet and outlet.

SHOULDER TO GAUGE RATIO

Accurate strain control in the testing environment is essential for proper fatigue testing procedures and reliable results. The Linear Variable Displacement Transducer (LVDT) is employed for this purpose, as it can function effectively in the testing environment (though other methods for controlling fatigue tests in this setting also exist). The traditional strain control method, which involves using an extensometer directly on the specimen's working part, is not feasible. To achieve the required deformation on the specimen's working part, the LVDT is clamped onto the specimen’s shoulders, and the displacement of the shoulders is used to control the experiment.
The relationship between the strain amplitude controlled on the specimen's shoulders by the LVDT extensometer and the strain amplitude on the specimen's working part is complex. This relationship depends on the required strain amplitude (ε_a), which varies throughout the test due to differences in the material's cyclic behaviour, such as cyclic softening or hardening on the working part, as well as the specimen's blend radius. Another factor influencing this relationship is temperature, though incorporating temperature effects is not straightforward (this factor is not addressed in this paper). Several methods exist for applying corrections to the strain length from the shoulder to the gauge (working part of the specimen), with the simplest being a correction factor commonly referred to as S2G (see Vankeerberghen et al.) or CC at ÚJV Řež, a. s. The difference between CC and S2G is minimal, with CC being the inverse of S2G. This correction factor is material-dependent (for a specific material type), as well as dependent on specimen geometry, loading amplitude, and the specimen fixtures in the autoclave. There are two methods for determining the CC: one is through experimental testing, and the other is by using Finite Element Method (FEM).
The CC or S2G amplitude ratio is defined by using formula (1):

$$CC = \frac{\Delta L . L_{work}}{\Delta P} \qquad (1)$$

where ΔL is extension of the working part of specimen, L_{work} is the length of working part of specimen, ΔP is displacement measured by LVDT extensometer.
Figure 3 shows an example of the measurement of calibration constants using a video extensometer at autoclave Pluto 6 (ÚJV Řež, a. s.). However, for the purpose of the experimental program, the calibration constants determined by FEM were used.

Figure 3. Experimental measurement of CC using video extensometer – ÚJV Řež, a. s.

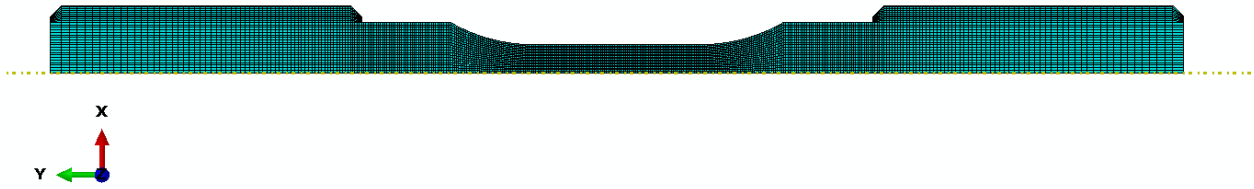

Figure 4. FEM model of the specimen geometry

ENVIRONMENTALLY ASSISTES FATIGUE TESTS (EAF)

Test was a strain-controlled tension-compression (R=-1) test, conducted in accordance with ASTM E606/E606M-21, ISO 12106 and EN ISO 11782, with modifications as required to allow testing under the required environmental conditions. The loading waveforms had a sawtooth profile. Fatigue life of the material was reported in terms of N25, i.e. the number of cycles required for the tensile stress to fall 25% from its peak or steady state value.

Table 2: Test matrix ÚJV Řež, a. s.

Specimen	Temperature [°C]	Pressure [MPa]	Strain amplitude [%]	Strain rate [%/s]
T16	320±4	12,5	±0,6	0,005
T17	320±4	12,5	±0,6	0,005
T18	320±4	12,5	±0,6	0,005

Table 3: Test matrix JRC Petten

Specimen	Temperature [°C]	Pressure [MPa]	Strain amplitude [%]	Strain rate [%/s]
T5	320±4	12,5	±0,6	0,005
T6	320±4	12,5	±0,6	0,005
T8	320±4	12,5	±0,6	0,005

POST TEST ANALYSES

All fractographic analysis was carried out using Tescan AMBER SEM (scanning electron microscope) in ÚJV Řež, a. s. The fracture area was analysed in detail using a Tescan AMBER SEM, including marking the initiation zone. Fracture surfaces of the specimens are mainly composed of fatigue fractures with the presence of striations which are a characteristic feature of fatigue damage.

Figure 5. Example of the fracture surface after EAF test – autoclave Pluto 6 (ÚJV Řež, a. s.)

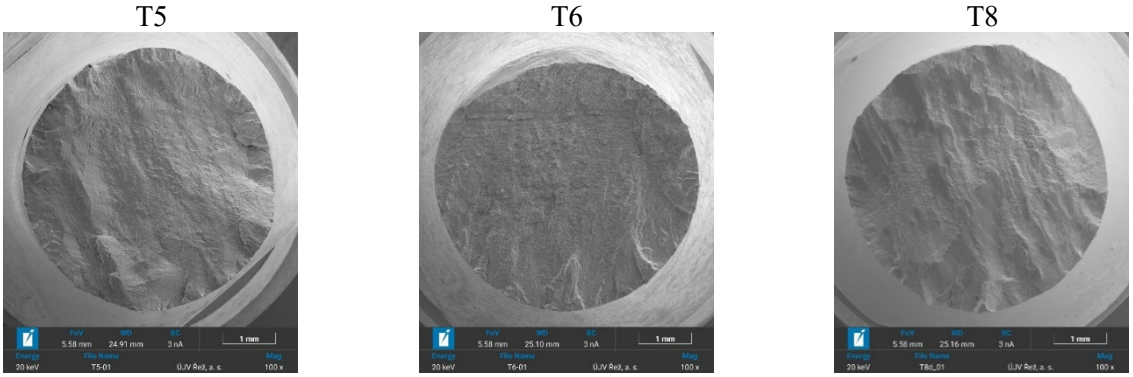

Figure 6. Example of the fracture surface after EAF test – Autoclave 1 (JRC Petten)

RESULTS

The results of the individual tests are given in Table 4 and 5. Strain amplitudes are different from required ones given in 3 and 4 because the calibration constant have been recalculated. Figure 7 shows results and compares them with the curve according NUREG/CR-6909 rev.1 for environment (320 °C, strain rate 0,0005 %/s) with environmental factor Fen=6,352, the curve for air is also shown in chart.

Table 4: Results of LCF tests in ÚJV Řez, a.s

Specimen	Temperature [°C]	Pressure [MPa]	Strain amplitude [%]	Strain rate [%/s]	N_{25}
T16	320,0 ± 0,1	12,500 ± 0,006	± 0,600	0,0050	303
T17	320,0 ± 0,1	12,500 ± 0,006	± 0,5937	0,0050	554
T18	320,0 ± 0,1	12,500 ± 0,006	± 0,5937	0,0050	523

Table 5: Results of LCF tests in JRC Petten

Specimen	Temperature [°C]	Pressure [MPa]	Strain amplitude [%]	Strain rate [%/s]	N_{25}
T5	320,0 ± 0,1	12,500 ± 0,006	± 0,606	0,0050	339
T6	320,0 ± 0,1	12,540 ± 0,006	± 0,598	0,0038	335
T8	320,0 ± 0,5	12,213 ± 0,016	± 0,614	0,0051	315

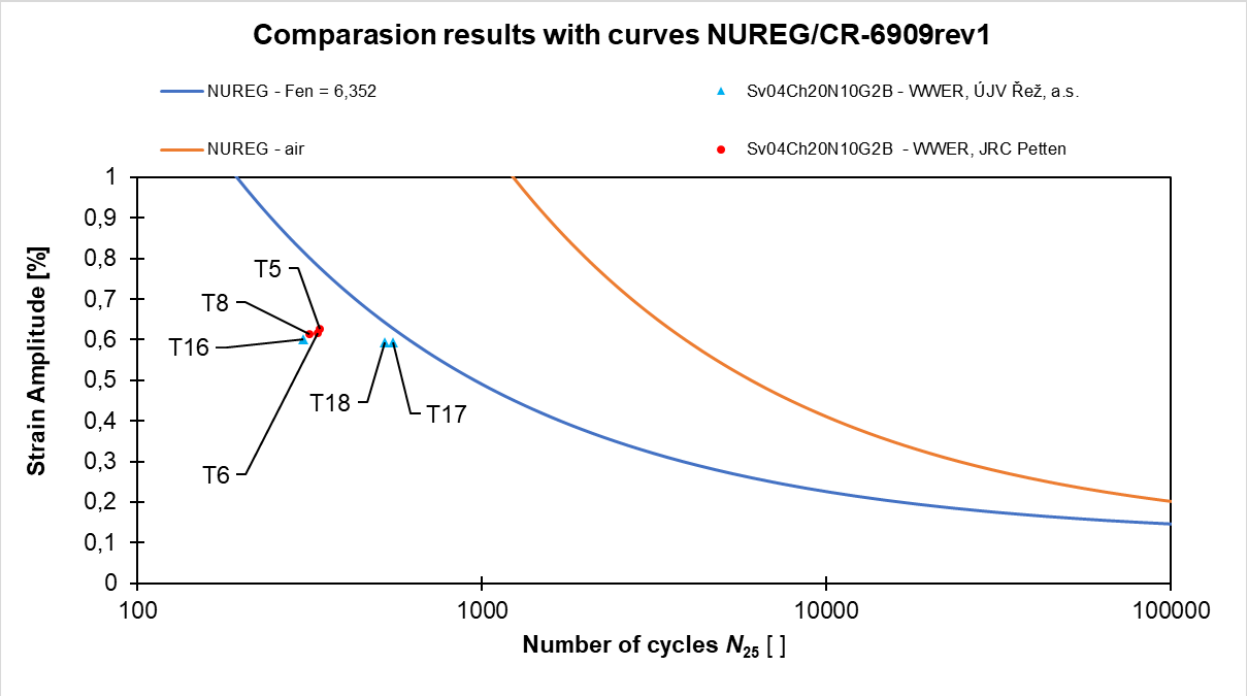

Figure 7. Comparison of N25 results with current valid test results from Sv04Ch20N10G2B material with the curve according to NUREG/CR-6909 rev.1 for environment (320 °C, strain rate 0,0005 %/s) with environmental factor Fen=6,352, the curve for air is also shown in chart

CONCLUSION

The evaluation of results of LCF tests in an environment of autoclave Pluto 6 at ÚJV Řež, a. s. and Autoclave 1 (JRC Petten) is summarised in Table 4, Table 5. The tables show the N_{25} values – number of cycles to failure, number of cycles at mid-life of specimen and total number of cycles performed.
As part of an interlaboratory comparison between the EAF test environments at ÚJV Řež, a. s., and JRC Petten, six tests were carried out, and the results were compared. The objective of the experimental program within the ENAFCLAD project is not only to expand the database of environmental fatigue tests but, more importantly, to compare results from laboratory tests conducted on two different experimental setups, using identical test parameters, maintaining consistent chemical environmental conditions, and employing specimens with the same geometry.
From the results obtained at ÚJV Řež, a. s. and JRC Petten, when the test parameters such as temperature, pressure, nominal chemical composition of the environment, and specimen geometry were kept the same, there was a strong agreement in the N25 values (the number of cycles to failure). The N25 results show clear consistency in the number of cycles to failure for the material Sv04Ch20N10G2B.

REFERENCES

ASTM E606/E606M – 21 (2021), *Standard Test Method for Measurement of Fatigue Crack Growth Rates.*
ČSN ISO 12106:2018 (2018): *Metallic materials - Fatigue testing - Axial-strain-controlled method.*
ČSN EN ISO 11782 – 1 (2009): *Corrosion of metals and alloys - Corrosion fatigue testing - Part 1: Cycles to failure testing.*
Vankeerbergehn, M., Mclennan, A., Simonovski, I., Barrera, G., Gomez, S. A., Ernestova, M., Platts, N., Scibetta, M., Twite, M. (2020). *"STRAIN CONTROL CORRECTION FOR FATIGUE TESTING IN LWR ENVIRONMENTS,"* Proc., Pressure Vessels & Piping Conference, PVP2020, Virtual.
Simonovski, I., et all. (2021). *"Calculated Shoulder to Gauge Ratio of Fatigue Specimens in PWR Environment,"* Metals, 11, 376: Doi: 10.3390/ met11030376 .
Chaboche, J.L. (2008*). "A review of some plasticity and viscoplasticity constitutive theories."* International Journal of Plasticity 24 (2008): 1642-1693. Doi: 10.1016/j.ijplas.2008.03.09.
White, C. S., Bronkhorst, C. A., Anand, L. (1990). *"An improved isotropic-kinematic hardening model for moderate deformation metal plasticity."* Mechanics of Materials 10 (1990) 127-147.
Chopra, O.; Stevens, G.L.: *"Effect of LWR Coolant Environments on the Fatigue Life of Reactor Materials."*; Technical Report NU-REG/CR-6909; Rev. 1, U.S. Nuclear Regulatory Commission (NRC): Rockville, MD, USA, 2018.
Gal, P.; Schnablova, I.; Pejsa, M,; Kopriva, R.; Cerny, J. (2024). *"Consideration of important effects in Environmentally Assisted Fatigue (EAF) of VVER austenitic steel components including cladding for the testing procedure improvement and update including the environmental factor. "; SMIRT 27, Yokohama, Japan 2024.*