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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

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ABSTRACT

The fatigue assessment of reactor internals and its parts and also of pressure vessel is of importance for aging management, safety and long-term operating of power plants. Current state of assessment account for lifetime (fatigue) influencing degradation effects, by application of reduction factors for fatigue lives curves, which are determined from laboratory tests. Some effects, as an environmental effect, are often considered with high level of conservatism or e. g. with the insufficient number of testing specimens. This can lead to non-conservative fatigue material behaviour, which is obvious from laboratory material testing, and lower fatigue lifetimes prediction of components compared with results based on design fatigue curves. ÚJV Řež, a. s. has been building the "infrastructure" for low-cycle fatigue testing including the environmental effect for long time from building the testing facilities through the testing and evaluation of the performed tests. Currently ÚJV Řež, a. s. is involved in numerous research programs, aiming to improve the understanding of environmental and loading effects on fatigue lifetime on relevant steels, welding and cladding materials used on VVER primary circuit.

ÚJV Řež, a. s. develops own testing autoclaves, capable of testing in aqueous environment and also on air using the inert atmosphere. Most of tests performed in autoclaves are strain-controlled, however the construction of experimental equipment does not usually allow the direct control of the applied deformation on the specimens and thus the LVDT sensor is used for this purpose. Therefore, it is necessary to calculate or measure the shoulder to gauge ratio (S2G) before testing. This ratio is dependent on applied strain amplitude and on type of tested material, construction of autoclave, specimen fixing etc.

Correct determination of S2G leads to better test execution and then for more accurate evaluation of fatigue life of tested materials and correct determination of environment factor, but also for better understanding of influence of environment (VVER coolant) on fatigue life of materials. For determination of S2G could be used the numerical methods like FEM and also is possible to use measuring procedure. Both methods will be presented within the paper.
The same materials used in Czech nuclear power plants (VVER 440 and 1000), with the same heat treatment and chemical compositions, were tested in numerous projects.

INTRODUCTION

For long term operation (LTO) on the current fleet of reactors is fatigue one of the main degradation processes, especially for operation longer than 60+ years. Taking into account the influence of environment is then essential part, because experimental data have shown significant negative effect of environment on fatigue life of steels used on NPPs e. g. the reactor internals and pressure vessel weld materials and cladding. There are several approaches and methods how to incorporate environment effect into fatigue analysis which was incorporated into national standards and e. g. US Nuclear Regulatory Commission Regulatory Guides (NUREG).

Developed methods for assessing environmental fatigue, as e. g. NUREG CR-6909 or NTD AME section III, could predict high usage factors which is not in accordance with actual plant

experience. Standards and guidance contain some conservatisms and one of them could be environmental factor (Fen). To characterize environmental effects on fatigue, especially austenitic materials, extensive test campaigns are performed in which the fatigue life under reference conditions (usually air at room temperature) is compared to the fatigue life in the environment. For this is necessary to use special devices where is possible to expose the specimen to the environment and perform the low cycle fatigue tests. Such a device is not very common, so ÚJV Řež, a. s. during the last two decades developed testing devices suitable for fatigue testing with environment. With this type of devices, called autoclaves Pluto 2 and Pluto 6, was ÚJV Rež part of international projects as a Incefa+ and is currently participating on project Incefa SCALE and also leading the national project "Design of fatigue life assessment of VVER type nuclear power plant equipment including impact of environment" focused on common VVER reactor materials.

During testing on autoclaves, is used cylindrical specimen, which could be used for classical fatigue analysis. So there are no problems with analysis of stresses or strains on specimens during testing. But there are different problems because the construction of autoclaves does not allow using the direct extensometers or tensiometers on working part of specimens. For correct measuring the stresses or strains is necessary to use different methods as a linear variable displacement transducer that are connected to the shoulder of specimens. Ideally the measuring devices would be placed at the working part of specimen, but this could lead to initiation of crack at the points of contact between extensometer and specimen on environment. The strain is then obtained from the displacement measured at the shoulder of specimen applying the shoulder to gauge (working part) ratio. This shoulder to gauge ration is required to know before testing, either by separate sets of tests in an air or by finite element simulations.

This paper is focused on the description of experimental autoclaves devices, description of shoulder to gauge ratio a how to obtain this ratio. Finally, some experimental results from tests which are compared with generic fatigue life curves.

TESTING DEVICES USING FOR FATIGUE INCLUDING THE ENVIRONMENT EFFECT

Autoclave tests are carried out in ÚJV Řež, a. s. using in-house developed autoclaves. For EAF have been developed two autoclaves named as *Pluto 2* and *Pluto 6*. On these autoclaves are possible to testing specimen including environment, mainly water with appropriate chemistry (VVER or PWR) but also testing on air which is simulated by an inert gas. Schematically is diagram of autoclave P6 shown on Figure 1. Maximal testing parameters on autoclaves (P2 and P6) are:

- Pressure: 12,5 MPa,
- Temperature: 325°C,
- Max. load: ±12 kN,
- Max. flow rate: 2 l/h
- Frequency of loading, only for EAF: < 0,05 Hz

Most tests are performed as a strain-controlled, which means during testing is constant amplitude of deformation.

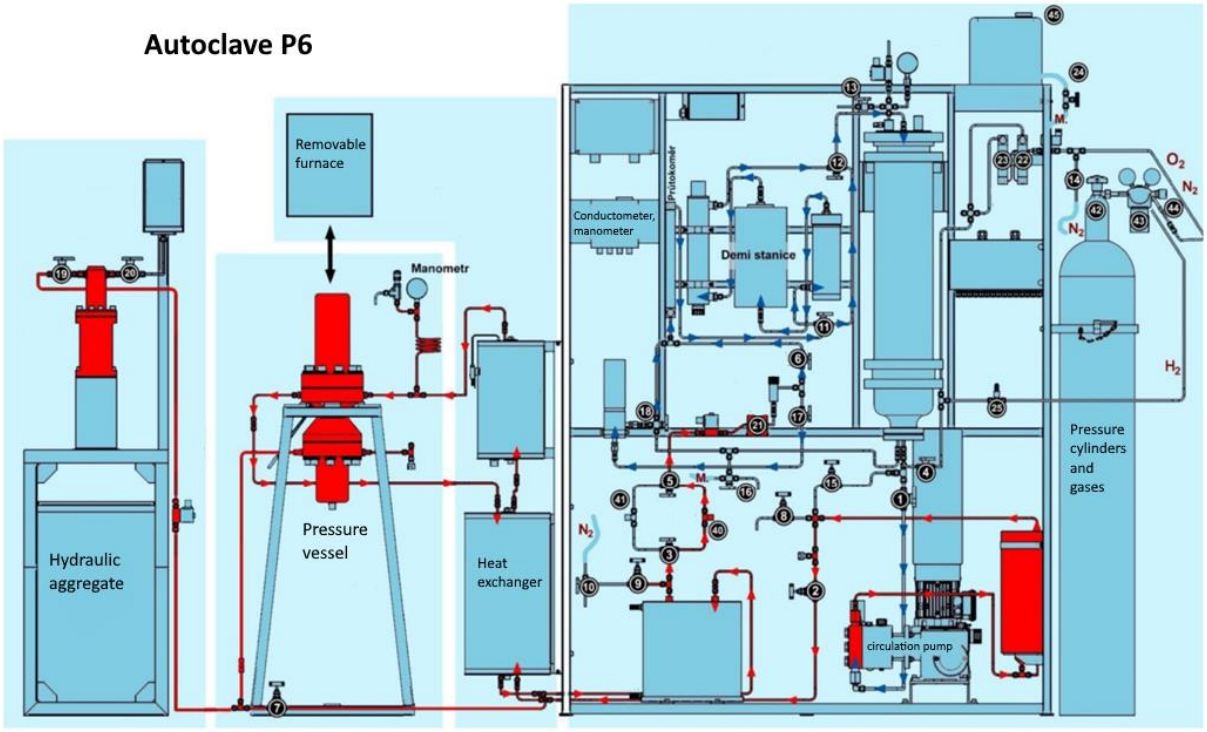

Figure 1. Diagram of autoclave P6.

The design of used UJV type specimen is shown on Figure 2. Cylindrical specimen with nominal diameter of 5 mm and nominal gauge length of 15 mm.. Surface of the gauge is polished.

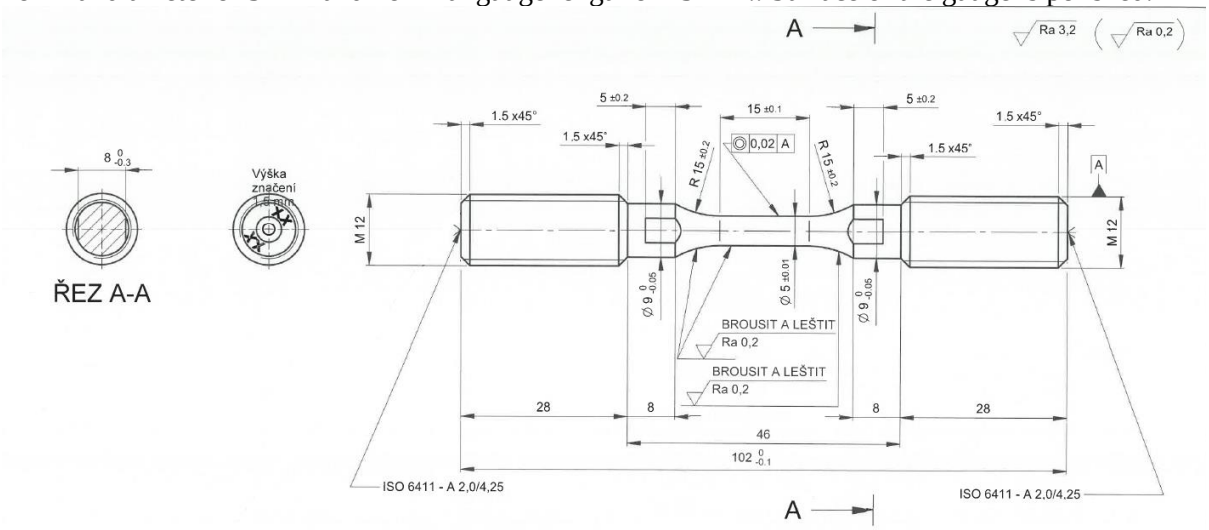

Figure 2. Specimen geometry for the EAF testing (UJV type)

SHOULDER TO GAUGE RATIO

Accurate strain control in the environment is needed for correct fatigue testing procedure and accurate testing results. The Linear Variable Displacement Transducer (LVDT) is used during testing for this purpose because is capable of operating in environment (there are more than this method for controlling the fatigue tests in environment). It is not possible to use the classical method of strain control using the extensometer placed directly into working part of specimen. To ensure the required deformation on working part of specimen, the LVDT is clamped on the shoulders of a specimen and the shoulders displacement is used to control the experiment.

The relationship between cyclic strain amplitude controlled on the shoulders on specimen by LVDT extensometer and the strain amplitude on working part of specimen is not simple. The relationship is dependent upon the required strain amplitude (ε_a) which is not same during the test and varies throughout a test due to differences in material cyclic behaviour as a cyclic softening or hardening on working part of specimen and specimen blend radius. Another parameter on which is dependent is temperature, but it is not easy to incorporate the temperature. There are a several methods to applying the shoulder to gauge (working part on specimen) length strain correction, but the simplest one, which is used during testing procedure is one correction factor which is commonly called *S2G*, see Vankeerberghen et all, or *CC* in UJV Rez, a. s. There is a small difference between CC and S2G, namely that CC is the inverted value of S2G. This correction factor is dependent on material (for one material type), specimen geometry, loading amplitude and on the specimen fixtures on the autoclave. There are two methods how to find CC. One is by experimental testing procedure and the second one is by using FEM. Both methods are described below.

The CC or S2G amplitude ratio is defined by using formulae:

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

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.

Obtaining the ratio by experimental measuring

The correction factor is generally derived in tests performed in air by cycling the specimens using a video extensometer - a camera with special software that evaluates the level of deformation using reference points on the specimen. The video extensometer is a noncontact, real-time, high strain-accuracy device which tracks surface markers or features and calculates strains by digital image correlation technology. Specimen working part usually needs to be sprayed with a contrasting colour, see Figure 4. The measurement of ratio CC on P6 is performed manually using special load fixture.

Figure 3. Experimental measurement of CC using video-extensometer.

Figure 4. Specimen after application of contrast colour.

Obtaining the CC ratio by FEM

Nowadays the FEM method is quite common to evaluate stress and strains on components and provides detailed insight into the behaviour structures. This method is also suitable for determining the CC ratio. Since the problem to be solved is not so simple and involves plasticity deformation, material information is necessary as a large hysteresis loops or cyclic deformation curve. For this information, material testing must first be performed. Material tests should by performed at the same loading rate and deformation amplitudes as the autoclaves tests. The use of the same parameters minimizes the error on calculating the CC. Because mainly are tested materials used for reactor internals and piping's, these are stainless steels which shown deviation from Masing´s behaviour, see Figure 5. This usually results from an unstable microstructure of the material during loading. This material effect strongly influences the simulation and play´s a role on choosing the correct modelling approach.

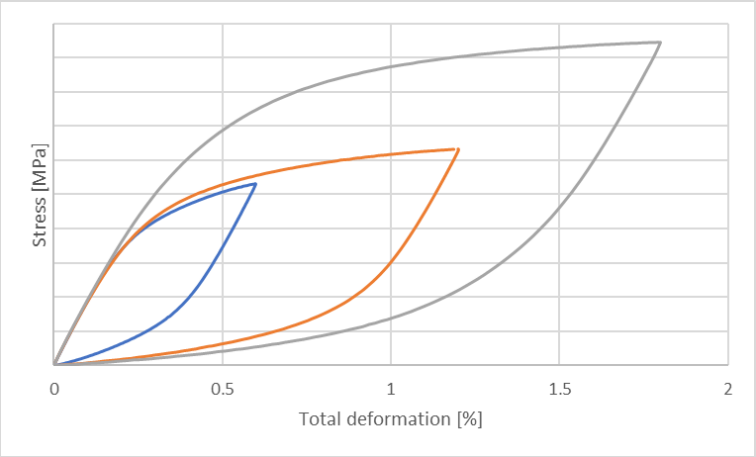

Figure 5. Deviation from Masing´s behaviour of 08Ch18N10T material.

For obtaining the CC ratio Chaboche computational model was used, see Chaboche 2008 which is the same methodology as was presented on paper Simonovski 2021. For obtaining the CC on saturated state, this methodology is sufficient. For obtaining the Chaboche material parameters the large hysteresis loops was used. For this case it is not appropriate to use cyclic deformation curve because it would create an error on amplitudes of deformation when the curve is not able to describe experimental points (deviation from Masing´s behaviour). So that for each strain level it uses the corresponding the large hysteresis loop. That means we have three sets of material parameters. For describing the large hysteresis loops is sufficient Chaboche model with three kinematic parts. The isotropic hardening is not involved on simulation. This model is unable to describe the transition behaviour of materials as a cyclic hardening and softening. Involving the Isotropic hardening is it possible to describe these phenomena, but for each tested amplitudes is necessary to calibrate new isotropic material parameters. That is not the purpose of this article, which focuses on the saturated state of material and computing the CC ratio.

The FEM model is used as a two-dimensional axisymmetric and the entire specimen is modelled. In addition, we model the upper nut to introduce his stiffness into the calculation. The lower hinge is replaced by boundary condition, which also serves as a loading part of model.

The computation was performed using Abaqus FEM software. For reaching the required deformation on working part of specimen, the user subroutine *UAMP* was develop. This user subroutine monitors the deformation during simulation and controls the total deformation on working part of specimen. For reaching the saturated state is simulated four cycles.

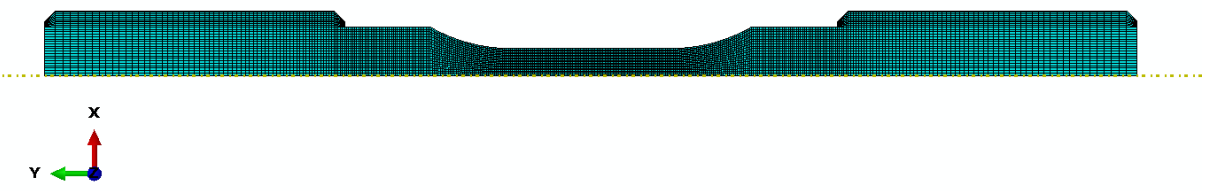

Figure 6. FEM model of specimen.

Above described used methodology is applicable only for symmetric loading behaviour, e. g. $\varepsilon_a = \pm$ 0,6%. This methodology is not sufficient for variable amplitude loading or for non-symmetrical cycles. During these types of loading plays the role mean stress relaxation effect. For this purpose, is necessary to use different kind of model, for brief information see White (1990).

Comparison of CC from experimental measurement and computational from FEM

Throughout our project, which will be described below on another chapter, emphasis has been placed on the validation of procedures and to find the best approach for obtaining the CC ratio. A lot of testing has been done to find pout the information about the behaviour of materials and this also allows us to compare the results from experimental measured CC and CC obtained from FEM computation. On Figure 7 is compared the results and shows that the result is in great agreement. The deviation between the two methods is less than 6%.

But provided results are not in agreement with results presented on paper Vankeerbergehn (2020), where is almost linear approximation curve used for different materials.

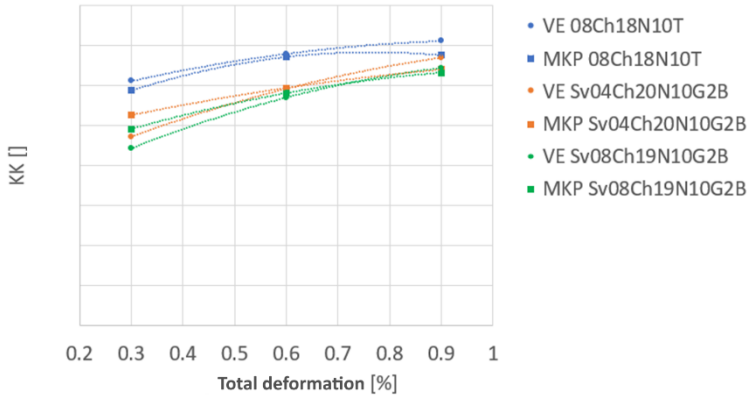

Figure 7. Results of ratio CC for different austenitic materials. VE means video-extensometer, MKP means computation by FEM.

ENVIRONMENTALLY ASSISTED FATIGUE (EAF)

Described methodology and testing devices are used for performing the test of material with influence of environment. There are several approaches to include environmental factor into fatigue assessment. Normally is the environmental factor marked as a Fen and this factor is defined as the ratio of fatigue life in an inert room temperature environment to the fatigue life in an environment on operating temperatures. To determine the factor is necessary to perform the tests on environment. During national project “Design of fatigue life assessment of VVER type nuclear power plant equipment including impact of environment“ (TITSSUJB039) is compared the results of experimental testing with generic curves listed on NUREG CR 6909 (Chopra 2018). During these projects are tested five austenitic materials on air and on VVER environment. The experimental testing is carried out with CC ratio described earlier. End of testing of specimens is defined as a decrease in force. On Figure 8 is listed some results for austenitic steel (purple dots) comparing with the generic curve from NUREG 6909. Is evident, that generic curve is slightly below the experimental results, so the Fen factor is higher than obtained from experimental results.

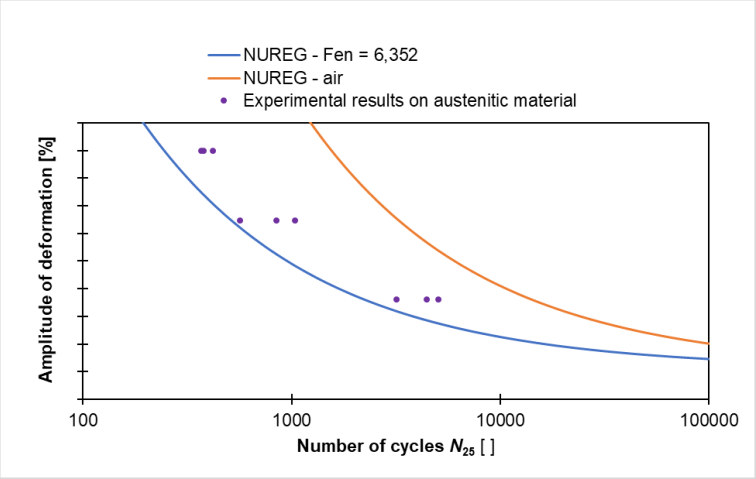

Figure 8. Generic design life curves and experimental results on environment.

CONCLUSION

On this paper were outlined some aspects of environmentally fatigue assessment of austenitic materials used on nuclear power plants. The main aim of this experimental testing is determination of Fen factor which describes the effect of environment on fatigue life. But this is the overall result of an experimental process in which many steps need to be completed for the result to be correct, e. g. determining the CC ratio, preparing the chemistry of environment, preparing the experimental devices and so.

Attention was paid to the determination of CC ratio which has direct impact to the quality of experimental results. Two methods for determining the CC ratio were presented. On future is an effort to use FEM method for determining the ratio and also include the effect of temperature, which could play important role.

The focus of Czech national program with a focus on environmental impact (TITSSUJB039) is to determine the Fen factor and compare these factors with generic curves on NUREG 6909. There are many other areas to which the project focuses.

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