A study of isothermal mechanical fatigue of welded reactor steel (15H2MFA)

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Abstract
As far as the reactor pressure vessel steel is concerned, the isothermal fatigue study of welded joints is helpful to protect the pressure vessel from blasting and save the life of its operators. Furthermore, the study helps to improve the future design of the reactor components and also enthuse to develop new materials. In material science, the fatigue of metal is quite difficult to deal with, and that of welded joint is an even more complex phenomenon. This complexity arises from different main factors: thermal cycles during welding, which will strongly affect the base material and induce residual stresses and distortion, the fusion process with the filler metal leads to heterogeneity to microstructure which will affect or change the original mechanical properties and chemical composition through out of the welded joint. In this study, isothermal mechanical fatigue of welded reactor steel has been contemplated. The samples of the welded joint used in this study are the '15H2MFA steel type of VVER-440' reactor pressure vessel operating at Paks Nuclear Power Plant, Hungary. The reactor vessel is made of low-alloy heat-resistant steel and austenitic steel with a corrosion-resistant inner (clad) surface.

Keywords Nuclear power plant · Reactor pressure vessel · 15H2MFA

1 Introduction
Unexpected age-related degradation of the mechanical properties of the reactor pressure vessel (RPV) steel can lead to safety concerns related to the mechanisms involved in ageing, which will help later in life extension process; these mechanisms include fatigue, irradiation embrittlement, thermal ageing, temper embrittlement, corrosion, where attempt of study focuses on fatigue. In this study, thermo-mechanical fatigue experiments took place for 15H2MFA using GLEEBLE-3800 physical simulator at isothermal condition, 260 °C, where the test is conducted under uniaxial tension–compression loading with total strain control to investigate its fatigue life. The low cycle isothermal fatigue results were evaluated with the Coffin-Manson law; the behaviour of fracture surfaces was observed using a scanning electron microscope (SEM). Nuclear power plant is one of the clean energies we have today in the world; however, it is non-renewable energy. It does not have a single impact on the environmental pollution. Nuclear energy now provides about 10% of the world’s electricity from about 450 nuclear power reactors in operation worldwide, total 398.9 GW(e) in net installed capacity, an increase of 2.5 GW(e) since the end of 2018. In 2019, nuclear power generated almost one-third of all low carbon electricity and was set to remain the second largest source of low carbon electricity after hydro power of the operating reactors; more than 51 are Russian designed VVER (pressurized-water) types, 16 of which are VVER-440/213 (second-generation VVER) reactors operating at the Paks Nuclear Power Plant (NPP). Most of these are nearing the end of their originally planned 30 years of operation. This RPV operates at high pressure and temperature 12.3 MPa, 297 °C respectively and includes the active core of the reactor, and associated pressure equipment is of paramount importance throughout the operating hours of the power plant, as their integrity ensures that radioactive media is checked and could not endanger the workers of the power

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plant, the residents and the environment. Therefore, a reactor pressure vessel must be able to withstand all loads resulting from the normal operating conditions of the reactor and possible malfunctioning conditions, without damage [1]. The core barrel, core baffle and protective tube unit are kept from lifting under normal operating conditions by their weight plus hold-down assemblies employing elastic components made of thermo-expanded graphite. This performs better than the materials used in the V-320 reactor (VVER-1200), with a service life of at least 4 years without replacement [2]. The fatigue phenomenon in welded connections, which significantly affects the useful life of metallic structures, is an important case study in the field of structural engineering. This phenomenon is induced by cyclic loadings able of causing the failure of a structural element at minor stress levels compared to the strength limit of the material itself [3–8]. Recurring thermal cycling (during start-up/shut-down and reactor trip conditions) in combination with mechanical loadings could lead to the buildup of thermomechanical fatigue (TMF) damage in components bare to elevated temperatures under service. Generally, isothermal low cycle fatigue (IF) tests performed at the maximum temperature (Tmax) of reactor operation are used to assess the performance of materials subjected to TMF loadings, owing to the simplicity associated with the former. However, thermal cycling in association with mechanical deformation has been reported to be more damaging compared to the isothermal mechanical strain cycling even at the Tmax of the TMF cycles [9–15]. The previous studies revealed that the low-cycle, thermal and mechanical stress were developed due to starting and shutting down operation of power plant and also transient power [16]. The region of joining in the welded joint was found to be weakest because of the differences in the chemical composition of filler material and base materials [17–22]. In the year 2013, Ashokkumar et al. examined compositional analysis for Fe–Ni ball milled powder and spark plasma sintered specimens [23]. In 1992, Sornette et al. reported that the ‘β’ value in the empirical relation of Coffin-Manson model \(N_R \Delta \varepsilon_p^\beta = C\) is to be 2 for single-phased metallic materials, with respect to their atomic and/or polycrystalline structure, where \(N_R\) is the cycles to fracture in the low-fatigue regime, and then amplitude of the applied cyclic plastic deformation is denoted by \(\Delta \varepsilon_p^\beta\). Furthermore, the law says that the product of \(N_R\) and \(\Delta \varepsilon_p^\beta\) is directly proportional to the constant ‘C’ [24]. The structural changes that occur in any material subjected to cyclic stresses and strains are called ‘Fatigue’. The results of these structural changes caused the formation of crack or fracture. This study carried out the comparison of cyclic load behaviours of 15H2MFA steel specimens under isothermal low cycle fatigue for varying strain amplitudes.

2 Experimental

The work carried out for this experimental study is illustrated by means of a flowchart, which is given in Fig. 1.
2.1 Critical examination of a metal block containing a seam

The welding seam used in the experimental work is illustrated in Fig. 2. The piece was made at the reactor vessel manufacturing plant at Skoda Power Plant in Plzen at the same time as the Paks reactor vessels were manufactured.

The material shown is 140-mm-thick Cr–Mo–V alloy steel with ferrite structure. The arrow-marked side is provided with titanium-stabilized chrome-nickel alloy with corrosion-resistant cladding. The raw material used for this study is 15H2MFA steel which is used in nuclear power plants. Tables 1 and 2 show the approximate chemical composition and mechanical properties of the steel 15H2MFA, respectively.

It is understood in the manual of the welded reactor (RPV VVER 440) that the welding technique of submerged arc welding (SAW) has been used for joining the parts in the pressure vessel. Sv-10ChMFT and flux An-42 were used as filler material and flux respectively. The specimen is characterized by the fact that it has a welding seam in its entire cross section. Prior to the preparation of the specimens, a macro-metallographic examination of the weld of the sample is carried out, for which the specimen is prepared as follows:

- Cutting the workpiece at the points marked with a red line in Fig. 2 taking care to mark the machining position with a pin on the surface of the workpiece.
- Planning and grinding of the surface marked with red arrow (cross section of weld seam), preparation for macro-metallographic etching.
- Polishing the surface marked with a red arrow in several steps, finishing with a sanding cloth of 1200, then polishing.

### Table 1 Chemical composition of test materials—15H2MFA (welded joints of RPV)

| Material | Composition [%] |
|----------|-----------------|
| C        | 0.13–0.18       |
| Si       | 0.17–0.37       |
| Mn       | 0.30–0.60       |
| S        | Max. 0.025      |
| P        | Max. 0.025      |
| Cr       | 2.50–3.00       |
| Ni       | Max. 0.040      |
| Mo       | 0.60–0.80       |
| V        | 0.25–0.35       |
| As       | Max. 0.05       |
| Co       | Max. 0.02       |
| Cu       | Max. 0.015      |

### Table 2 Mechanical properties of test materials 15H2MFA (welded joints of RPV) at 20 °C and 350 °C

| Materials       | Mechanical properties |
|-----------------|-----------------------|
| Temperature at 20 °C          | 540                   |
| Tensile strength [MPa]       | 431                   |
| Yield strength [MPa]         | 14                    |
| Elongation [%]              | 50                    |
| Reduction area [%]           | 490                   |
| Temperature at 350 °C        | 392                   |
| Tensile strength [MPa]       | 13                    |
| Yield strength [MPa]         | 50                    |
| Elongation [%]              | 50                    |
Development of a polished surface fabric structure with 8% Nital etching agent. Macroscopic cross-sectional view of the welded region is illustrated in Fig. 3. It shows the result of metallographic etching.

The structure of the multilayer, sealed seam and the heat effect zone are illustrated in Fig. 4. Having a macro-metallographic image, it can determine the exact location of the specimens to be machined.

In addition to knowing the structural homogeneity of the suture, the homogeneity of the composition of the seam is essential to determine the number of specimens required for the fatigue tests. To determine the alloy content distribution along the seam, a numerical sampling at the locations indicated in Fig. 5 was performed for composition analysis. Composition testing was performed at Dunaferr Zrt’s Metallographic Laboratory using ICP-OES composition testing equipment. The test required 5 g of chips, which were obtained by drilling with 12 to 15-mm-deep perpendicular borehole drill bit.

Based on the obtained results, it can be shown that the weld seam has a uniform distribution across its entire cross section except for the first fill line.

### 2.2 Determination of typical dimensions of test specimens

Based on the above data and bearing in mind the sample geometry required by the GLEEBLE 3800 simulator described above, the dimensions of the fatigue specimen required for testing were determined. There is limited space in the physical simulator chamber, which should be considered when designing the specimens. The specimens shall be compatible with the clamping system of the equipment and shall withstand the high compressive load.
stresses without bending. The specimens formed exhibited cracks at the transition between the cylindrical section and the rounding, which is one of the disadvantageous results due to the resistance heating and heat removal of the clamping jaws; a slightly decreasing temperature distribution in the specimen is axially decreasing to the two sides of the thermocouple providing the control signal, so that damage at the desired radius does not occur. By modifying the geometry of the specimen, it was necessary to ensure that the cracks in the cylindrical section were formed with certainty. By modifying the geometric model, it has been demonstrated that using a 10-mm radius reduces this effect to the desired level, so the dimensions of the specimen have been modified and made further test measurements. It is clearly visible that each of the 10-mm rounded specimens had a crack in the middle third of the cylindrical section, as shown in Fig. 6.

The samples used for the experiment are made of 13-mm edge-length square column prefabricated on the CNC lathe. Before the start of the tests, all samples have been polished to the same surface grade on conventional lathes to minimize the impact of the surface irregularity from production on the wearable test results. Samples have been prepared for the fatigue test according to ASTM E466-15 (2015) [25]. The 2D geometry of the sample is shown in Fig. 7.

### 2.3 Manufacture of test specimens

Based on the specimen enclosure dimensions and the size of the welded block, the welding splitting plan is determined. The eighty pieces of samples were prepared by marking their exact location with an (X, Y) coordinate and for those that their position in the seam can be accurately identified and manufactured. Barcode label is given to all samples selected for fatigue test to identify them during the operation. In the first phase of cutting, a section parallel to the weld cross section was cut and subjected to repeated metallographic examination. The purpose of this is to make the weld contour and the heat effect zone visible and to facilitate hardness measurement. It is impossible to evaluate directly the fatigue behaviour of heavy machine members from the laboratory test results on small specimens. The majority of materials are having size effects. The fatigue strength of larger size is lower than that of smaller size. Accurate finding of this fact is difficult. It is very hard to prepare geometrically similar specimens of large diameter that have the same metallurgical structure and residual stress distribution throughout the cross section. The exertions in fatigue testing of large specimens are considerable, and few fatigue machines can accommodate specimens with a wide range of cross sections [26].

### 3 Results and discussion

#### 3.1 The experimental results and their evaluation

From the data recorded during the isothermal fatigue tests, the relation between force, temperature and time is shown using the graph below in Fig. 8. The constant temperature (isothermal) was about 260 °C which is marked by a red line. This is when strain, force and temperature data were sampled at 100 Hz. for a 0.6% total strain load. The data presented are derived from the cyclic mechanical behaviour of the fatigue tests, and analysing the measurement data, it was found that the prescribed time function of the physical quantities and the measured values showed a very good agreement for all settings.
3.2 Cyclical mechanical behaviour of experimental substances

The cyclical mechanical behaviour of the material is an important factor in deformation of strained-controlled low-cycle fatigue tests. The softening or hardening at the initial stage of the tests and the intensity of these depend on various parameters like strain, amplitude and strain rate and determining the voltage level at which the test is performed when entering the stable phase of the fatigue test. The extreme values of the voltages as a function of cumulative damage are shown in Fig. 9. It is observed from Fig. 9 that the crack formation occurred at the largest number of cycles with the application of the lowest TSA (0.6%). Crack formation occurred at the lowest number of cycles with the application of highest TSA (1.5%).

The cyclical mechanical behaviour of 15H2MFA material is similar to that of regular centre lattice steel with similar strength. During the initial phase of the tests, it showed intense cyclic softening, followed by a secondary softening phase during the stable cycles, which lasted until the appearance of a macroscopic size crack. The appearance and propagation of the crack may be related to the starting point of the definite reduction which is shown in Fig. 9.

3.3 Evaluation of measurements by Coffin-Manson

This is also called strain-based evaluation which is predominantly used to characterize low cycle fatigue behaviour of materials operating at elevated temperatures and high levels of stress observed in power plant during operation and start-up or shut-down procedures. In these conditions, fatigue damage is generally caused by plastic strain which can be clearly shown by Coffin-Manson law as below.

\[ \varepsilon_p = \varepsilon_f^* \cdot N_f^{1/2} \]
Here $\varepsilon_p$, plastic strain amplitude; $\varepsilon_f$, fatigue ductility coefficient; $N_f$, cycles to failure; and $c$, fatigue ductility exponent. To evaluate the experimental data using the Coffin-Manson model, the amplitude value of the plastic deformation was determined per load level, and the curves for each fatigue work order are shown by regression, as shown in Fig. 10, and Coffin-Manson model’s parameters of 15H2MFA are listed in Table 3. The fitted lines for experimental data and the Coffin-Manson model are much closer to each other. The values of $\varepsilon_f$, fatigue ductility coefficient and $c$, fatigue ductility exponent are determined as 1.0479 and $-0.7375$ respectively.

### 3.4 Fractographic analysis

There are three stages of fatigue fracture: initiation, propagation and final rupture when the material is incapable to withstand the load at a given cycle. From the samples of 15H2MFA steels that have undertaken isothermal fatigue test, the tested samples usually have one or more major cracks and several smaller ones. The major cracks often originated at the joint between the thermocouple and the test bar. The number of large developed cracks decreases with increasing total strain amplitude (TSA), while the number of smaller cracks grows which is the developing of fatigue cracks, and these focused near the ends of the main cracks and form different branches as the number of cycles or load increases as shown in Figs. 11, 12, 13 and 14. The origins of the cracks are located on the sample that had undergone fatigue test, and they have got a semi oval shape which can be clearly seen in Figs. 15, 16, 17 and 18. The appearance of the fracture surface is fine grained and covered with a very fine blue oxide layer. The total length of major cracks can extend up to 3–4 mm where striations were not so prominent, as is typical for ferrite steels, and the distances of them are very short at the beginning of the crack and become coarser with increasing crack length (Figs. 19 and 20). The distance between striations firstly rises and subsequently decreases dependent on the length of crack with increasing the total strain amplitude. In this section, the selected samples allowed to be broken at the large crack that is vividly seen without using magnifying glasses appropriately without damaging the crack since the target of the study is all about the formation and condition of fatigue cracks using a scanning electron microscope (SEM), then by registering the code of the samples and attaching them to the SEM sample holder and inserting into SEM. In the next step, the program is started from the computer, and after the suitable vacuum is created the study of the samples intensely commenced. Finally, from the following pictures, it can be clearly understood the formation of the development of fatigue cracks using the pictures below taken by SEM for the 15H2MFA steel of different TSA and number of cycles ($N_f$) to failure. The regions of fatigue striations, crack initiations, crack growths, ultimate tensions are

### Table 3 Coffin-Manson model parameters of 15H2MFA

| Material | $\varepsilon_f$ | $c$   |
|----------|-----------------|-------|
| 15H2MFA  | 1.0479          | $-0.7375$ |
Fig. 11  Fatigue crack development of test bar, ISO, \( N_f = 420 \), TSA = 0.6%

Fig. 12  Fatigue crack development of test bar, ISO, \( N_f = 380 \), TSA = 0.9%
Fig. 13  Fatigue crack development of test bar, ISO, $N_f=201$, TSA = 1.2%

Fig. 14  Fatigue crack development of test bar, ISO, $N_f=112$, TSA = 1.5%
Fig. 15 Fracture surface of cracks, ISO, $N_f=420$, TSA = 0.6%

Fig. 16 Fracture surface of cracks, ISO, $N_f=380$, TSA = 0.9%
Fig. 17 Fracture surface of cracks, ISO, $N_f=201$, TSA = 1.2%

Fig. 18 Fracture surface of cracks, ISO, $N_f=112$, TSA = 1.5%
Fig. 19 Fracture surface near crack initiation region, ISO, $N_f = 464$, TSA = 1.2%

Fig. 20 Fracture surface in crack growth region, ISO, $N_f = 464$, TSA = 1.2%
4 Conclusions

The isothermal low cycle fatigue behaviours of welded joints of reactor pressure vessel steel material 15H2MFA were investigated holding isothermal temperature at 260 °C under fully reversed wholly controlled strain. The major results are given below:

1. The isothermal low cycle fatigue tests yielded a higher fatigue life than any other thermo mechanical testing where cyclic softening has occurred in the 15H2MFA steel during the test.
2. Cracks commonly occur in engineered parts and can significantly reduce their ability to withstand load, and cracks typically form around pre-existing flaws in a part. It usually starts off small and then grows during operational use.
3. The number of large developed cracks decreases with increasing total strain amplitude (TSA), while the number of smaller cracks grows which is the developing of fatigue cracks, and these focused near the ends of the main cracks and form different branches as the number of cycles or load increases.
4. It is apparent that to ensure sustainable safe operation of the ageing reactor units, the detail understanding of different damage mechanisms and their effects in the structural materials of the respective nuclear power plant is significant.

Availability of data and material  The data reported in this manuscript were obtained from the experimental study.

Code availability  Not applicable.

Declarations

Consent to participate  We understand that if we have any additional questions about the study or our rights as a research participant, we may contact through our email.

Consent for publication  We give our consent for the publication of identifiable details, which can include photograph(s) and/or videos and/or case history and/or details within the text (‘Material’), in the above Journal and Article.

Competing interests  The authors declare no competing interests.

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