Utilization of Non-Destructive Methods for Monitoring Fatigue Crack Growth in Power Plant Material

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Abstract
A methodology for non-destructive evaluation of the fatigue crack growth behaviour by acoustic emission and potential drop technique has been proposed. A nuclear Cr–Ni–Mo–V ferritic steel, known as GOST 15Ch(Kh)2NMFA, has been chosen for this study. This material is used for the production of a key component of a nuclear power plant - reactor pressure vessel type VVER-1000. The serviceability of pressure vessels and piping is determined by the mechanical properties of the steels being used and, in particular, by the cyclic crack resistance of the base metal and its welded joints. Therefore, the main goal of this work is to propose a suitable methodology to predict a fatigue crack growth behaviour and to simulate the material behaviour during pressure test using non-destructive techniques. The acoustic emission monitoring has been used, together with electric potential difference measurements for monitoring crack growth, to correlate the signal parameters (such as the acoustic emission counts, evolution of the frequency spectrum and the energy) and the waveform-based analysis with the defect formation mechanisms and to provide a quantified estimate of failure probability. It has been found that most of the acoustic emission hits at loading frequency of 10 Hz and stress ratio of 0,1 are generated during the decrease phase of the loading force (crack closure), especially in its lower half, and less hits are generated during the increase phase of the loading force (crack opening). The results showed that non-destructive techniques used in this work can be very useful to fatigue crack growth assessment in Cr-Ni-Mo-V steel.

Keywords: acoustic emission, potential drop, fatigue crack growth, power plant material

1. Introduction

The degradation of mechanical properties of a reactor pressure vessel material, which determine the operational safety and remaining lifetime, is associated with microstructural changes induced by embrittlement and fatigue damage. In the conditions of cyclic temperature changes, as a result of start-ups and shut-downs of the power generation unit, this may lead to material crack initiation, in particular in the region of welded joints, edges of openings in steam blowdown and inlet connections, as well as in parts of pipeline installations [1, 2]. These are the reasons for which an assessment of the structural components’ lifetime requires the knowledge of fatigue properties of the power plant’s materials, determined in conditions similar to the operating conditions on the installation [3].

The evaluation of early fatigue damage and thus the prediction of the remaining lifetime is a task of practical relevance for example in the chemical, nuclear, as well as in the aircraft industry [4]. Moreover, the current challenging reliability and safety requirements are not realizable without an effective means of non-destructive testing (NDT) that would be used to monitor the condition of reactor pressure vessel materials, so far as NDT results reliably correlate with mechanical properties and relevant components are accessible [5]. The most appropriate NDT method for studying material deformation under fatigue loading is the acoustic emission (AE) technology. AE may be defined as the pressure or stress waves
generated during dynamic processes in materials. Most of the published work is directed to plastic deformation and initiation and propagation of cracks. Regardless of the phenomenon studied, material used, or the application, one point becomes obvious; the AE analysis is very sensitive to local transient instabilities. The material system will proceed towards its lowest energy state, and (in most situations) will develop unstable conditions locally well before the whole mass becomes unstable. These conditions result in local dynamic movements, such as formation of a slip-band or platelet of martensite, propagation of a crack or Lüders’ line, or sudden reorientation of a grain boundary [6]. Especially under high-cycle fatigue (HCF) conditions, more than 90% of lifetime is spent before cracks are usually detectable. The reason for this is a generation of small and subsurface cracks created by fatigue-induced compressive stresses within the surface region. Under HCF conditions very small non-detectable cracks can become unstable and result in a catastrophic failure [4].

Specifically for the field of metals, mainly the cumulative AE activity is utilized, being related to strength in single fibre fragmentation tests [7], as well as to the remaining lifetime in fatigue tests of steel specimens with notches [8, 9]. AE has also been used to clarify the moment of crack nucleation in indentation experiments [10]. For example, Aggelis et al. in [11] have obtained correlations between basic AE parameters with damage accumulation and the fracture mode. The AE behaviour shows that certain characteristics undergo clearly measurable changes much earlier before the final fracture emerges. Specifically, among others, the duration and the rise time of the signals, as well as the RA value\(^1\) of the waveforms increase sharply approximately 1000–1200 cycles before final failure. Consequently, AE offers the ability to detect and anticipate fatigue crack propagation accurately and provides an early warning to fracture and is a very useful tool of the fatigue assessment.

2. Experimental procedure

2.1 Materials and mechanical testing

<table>
<thead>
<tr>
<th>Material</th>
<th>C</th>
<th>Mn</th>
<th>Si</th>
<th>P</th>
<th>S</th>
<th>Cr</th>
<th>Ni</th>
<th>Mo</th>
</tr>
</thead>
<tbody>
<tr>
<td>15Ch2NMFA</td>
<td>0,15</td>
<td>0,50</td>
<td>0,23</td>
<td>max 0,02</td>
<td>max 0,02</td>
<td>2,1</td>
<td>1,1</td>
<td>0,60</td>
</tr>
</tbody>
</table>

Table 1. Chemical composition of 15Ch2NMFA steel

<table>
<thead>
<tr>
<th>Material</th>
<th>E (GPa)</th>
<th>(R_{0,2}) (MPa)</th>
<th>(R_m) (MPa)</th>
<th>A (%)</th>
<th>Z (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15Ch2NMFA</td>
<td>208</td>
<td>540</td>
<td>639</td>
<td>22</td>
<td>76,5</td>
</tr>
</tbody>
</table>

Table 2. Mechanical properties of 15Ch2NMFA steel

The material used in this study was a nuclear Cr–Ni–Mo–V ferritic steel, known as GOST 15Ch(Kh)2NMFA, whose chemical composition and mechanical properties are shown in Tables 1 and 2 respectively. The specimens were supplied in the form of compact tension specimens (CT50) which were obtained from the forged ring of the reactor pressure vessel. Microstructure of the studied material, due to the applied heat treatment, is a mixture of...

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\(^1\) RA value = Rise Time / Amplitude (of a hit)
heterogeneous bainite and martensite (see Figure 1). The geometry and basic dimensions of the CT specimen used are shown in Figure 2.

The fatigue tests were conducted on an MTS Systems Corporation servo-hydraulic machine with maximum load of 500 kN under room temperature. The fatigue cycle was sinusoidal with frequency of 10 (0.1) Hz, stress ratio R = 0.1 and load range 6-60 (5-50) kN. Applied load range was determined from the geometry of the test specimens and material properties, and remained fixed throughout the tests. The tests were continued until the specimens failed ultimately due to unstable crack growth or fracture.

![Figure 1. Specimen geometry and its basic dimensions [mm]](image)

![Figure 2. Microstructure of 15Ch2NMFA steel](image)

**2.2 Acoustic emission and crack propagation rate measurements**

AE monitoring of fatigue crack propagation was performed using the advanced modular XEDO system (frequency bandwidth 20-800 kHz) and the IPL system with continuous AE signal recording capabilities, supplied by the DAKEL Company (see Figure 3). Two piezoelectric sensors (MDK13 - DAK 432 piezoceramic, sensing face material: nickel coated FeNdB, magnetic disc, diameter 12 mm, DAKEL) were attached on one side of the specimen and other two directly opposite to them (see Figure 4). The AE data were processed with two-channel AE analyser (XEDO) with an I/O card included for crack growth measurement or recording of the loading force and there was also the four-channel AE analyser (IPL), which was used to obtain recording for detailed data processing.

AE data were collected, stored and analysed using the DAKEL Daemon (XEDO), DAKEL DaeShow (XEDO) and DAKEL-UI (IPL) software.

The count rate, amplitude, energy and the number of AE hits were considered among all AE parameters the most direct reflection of microstructural variation in materials. Results also include linear AE source location and analysis of the number of acoustic waves. The linear AE
source location provides locations from which AE events were generated. Location of the AE source is determined from the time difference between arrival of corresponding acoustic waves to two sensors placed at known positions.

![AE diagnostic system DAKEL IPL (a) and DAKEL XEDO (b)](image)

**Figure 3.** AE diagnostic system DAKEL IPL (a) and DAKEL XEDO (b)

The potential drop (PD) technique is based on injection of currents into the examined object and measurement of the resulting voltage difference between two points on its surface. The capability of measuring hidden cracks and the possibility of full automation of the measuring process belong to the main advantages of this technique. Downside of this technique is the fact that the measured specimen has to be electrically conductive, otherwise the technique does not work. In this study, the PD technique has been used for monitoring fatigue crack growth rate using the TECHLAB SRT-KK.2 device.

In this simple technique, electrical direct currents are injected into the conducting specimen through one pair of electrodes, while a second pair straddles the crack (or a small monitoring area where crack initiation is expected). A schematic illustration and an experimental setup of PD measurement is shown in Figure 5.
3. Results

3.1 Acoustic emission response during fatigue loading

AE measurement was carried out on several specimens under the same conditions. In the rest of the paper we present the AE response of specimen “CT15Ch2-PL36” under fatigue loading. Since the fatigue test was interrupted several times due to pressure test simulations, the results will be demonstrated in three phases of fatigue life. Figure 6a shows a course of the crack growth rate using the PD technique (black line). The rate increases exponentially, as typically expected in metal fatigue. AE in stage I should correspond to the fatigue crack initiation. At the beginning of the test, the crack formation and plastic deformation sources at the tip of the notch generate intense AE events, which contributed to rapid growth of AE counts. After the crack initiation (at 50 min position), the AE signals in stage II are associated with fatigue crack propagation. Generally, the fatigue crack propagation is characterized by highly fluctuating AE activity throughout the test. The crack length was about 11.7 mm at the end of the first phase of measurement (see Figure 6b).

In the first phase, duration and rise time of the AE hits depend on the loading force, as given in Figure 7. One can easily see, that in the crack initiation stage, the AE hits are generated in the entire range of the loading force and that they create clusters at maximum load and also at lower load levels in the second stage, respectively. This could mean that the emissions in stage II were mainly generated by dislocation activities in the plastic zone.
To investigate correlation between the crack propagation and AE hits, the filtered AE data were separated into falling and rising phase of the loading force. In order to understand the AE generated in all phases of fatigue loading, the AE amplitude and duration distribution analysis has been performed. Figure 8 shows histogram of the AE amplitude and duration in the first phase. Most of the AE signals are generated in the falling phase of the loading force with amplitude of about 69 and 71 dB\text{AE} and duration of about 600 \( \mu \text{s} \), respectively. AE hits generated in the rising phase of the loading force have the highest frequency amplitude at about 71 dB\text{AE} and duration of about 200 \( \mu \text{s} \), respectively. Generally, AE hits have shorter duration and rise time in the rising phase than at falling phase of the loading force, as shown in Figure 9.

Figure 7. Time history of the AE hits depending on the loading force in the first phase: (a) duration, (b) rise-time

Figure 8. AE amplitude (a) and duration (b) histogram in the falling / rising phase of the loading force in the first phase of the fatigue loading

Figure 9. Time history of rise time in the falling / rising phase of the fatigue loading in the first phase of the measurement
Development of the AE signal for next phases of fatigue loading is shown in Figure 10 and 11. Compared to the previous phase, the rise time starts to exhibit increasing tendency (indicated by the red arrow in Figure 10) in the second and third phase.

![Figure 10](image1.png)  
Figure 10. Evolution of rise time during the falling and rising phase of the load force in the second (a) and third (b) phase of the measurement.

The total crack length was about 14.1 mm at the end of the loading. Increasing rise time parameter and changes in the frequency of occurrence as another parameter in the time during the falling or rising phase of the loading force (see Figure 11) may indicate possible shift of the cracking mode from tensile to shear or changes in crack propagation rates from slow to fast (or stable to unstable). A typical example of the AE hits generated in the second and third phase is displayed in Figure 12. However, the AE transition could also be caused by changes in the fracture mode, as is shown in Figure 13.

![Figure 11](image2.png)  
Figure 11. Duration histogram of fatigue loading in the falling / rising phase of the loading force in the second (a) and third phase (b).

![Phase II](image3.png)
3.2 Acoustic emission response during pressure test simulations

The aim was to simulate the AE response to static pressure loading which is applied during the pressure tests of nuclear power plant components. The experiments were carried out on the same CT specimens at the beginning and end of the second phase of the fatigue loadings. The phase of increasing pressure was simulated by an extension of the short crack before the first phase of fatigue loading and the long crack after the first phase.
The “pressurization” schedule to be raised in steps with pressure holds between the steps up to the maximum force (simulating pressure) of 90 kN. Followed by the decreasing pressure phase and the second holding period (see Figure 14). It was confirmed that in case of long cracks the AE hits increase during the pressure holds (see Figure 14a) and in case of short cracks the occurrence of AE hits is low. Typical examples of AE hits generated in various stages of the pressure test is seen in Figure 15.

![Figure 15](image1.png)

**Figure 15.** Typical AE waveforms detected in the phase of increasing force (pressure) at maximum (a), holding force (pressure) (b) and decreasing force (pressure) at -10 kN (c, d)

The scanning electron micrograph of the fracture surface as shown in Figure 16a demonstrates all phases of the fatigue life with the static overload bands, i.e., the places of a local plastic deformation (stretch zones). The pressure test simulations helped us better understand the mechanical behavior of the damage and crack propagation with combined usage of the fractography and the AE.

![Figure 16](image2.png)

**Figure 16.** Overview of the fracture surface (a) and detail of the static overload at the second pressure test (b)
4. Conclusions

The work correlates the results of the electrical potential difference method and the acoustic emission to obtain, first, a classification of the different stages of the crack propagation and, second, by an AE advanced analysis to obtain AE identification of the different crack propagation mechanisms. This study shows the effectiveness of the non-destructive testing method by acoustic emission to detect different stages of fatigue crack propagation. Results indicate that the relationship between the count rate and crack propagation rate is nonlinear (see Figure 6). However, advanced analysis (such as the duration, amplitude) has shown a very clear trend. To investigate correlation between the crack propagation and AE hits, AE data were separated into falling and rising phases of the loading force. Most of the AE signals are generated in the falling phase of the loading force. On the other hand, AE hits have a shorter duration and rise time in the rising phase of the loading force in the first phase of the fatigue loading (see Figure 9). However, compared to the first phase, the rise time starts to exhibit increasing tendency (indicated by the red arrow in Figure 10) in the second and third phase, and it can be used as an indicator of changes in the fracture mode or in the crack propagation rates from slow to fast (or stable to unstable). The basic result of this investigation is that the count rate, amplitude, rise time, duration and average frequency are the important parameters for AE identification of different crack propagation mechanisms.

The pressure test simulations in this work gave us an understanding of the mechanical behaviour in terms of damage and crack propagation and the joint use of fractography as well as acoustic emission confirms identification of acoustic signatures of various phenomena of damage. Results of performed experiment provide a database allowing identification of fatigue damage and shows that non-destructive techniques used in this work may be very useful to fatigue crack growth assessment in pressure vessel materials.

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References


