Assessment of Early Fatigue of Power Plant Material Using Acoustic Emission Method

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Abstract
This work presents the application of the acoustic emission technique for detection and characterization of early fatigue damage. Specifically various manifestations of the localized plastic deformation that is the precursor of microcrack formation. A nuclear Cr-Ni-Mo-V low-alloy steel has been chosen for this study. The acoustic emission signal has been correlated with the defect formation mechanisms and the registration of loading (resonant) frequency changes of the tested specimen taken by RUMUL fatigue machine. The work is focused on the analysis of the acoustic emission signal during opening and closure half-cycle.

Keywords: fatigue behaviour assessment, acoustic emission, crack initiation, power plant material

1. Introduction

Statistical evidence shows that up to 40% of various energetic equipment is caused or accompanied by pitting, fatigue or corrosion [1]. That is why is necessary to study and understand mechanisms of corrosion and fatigue behaviour of these component especially in nuclear power plants. This work is focused on fatigue behaviour of 15Ch2NMFA low-alloyed steel which has been used since 1975 as a material for pressure vessels. The reactor pressure vessel is one of the most important parts of nuclear power plants which have to satisfy strictest safety, reliability and operating economy requirements. Most important properties of pressure vessel materials are - brittle failure resistance, fatigue resistance, crack growth resistance and metallographic purity [2].

As mentioned, operability of pressure vessels depends on mechanical properties of used material, which has to satisfy strict requirements on crack growth resistance of basic material and its welded joints. As the temperature decreases from the working level (250 – 300 °C) to temperatures of transient modes (during a shut-down or a start-up of a reactor) corrosion processes can be more active [3]. During operation (30 to 40 years) of pressure vessel, strength properties values increase and ductile properties decrease (due to radiation and hydrogenation). That is why probability of brittle crack failure rises.

The current challenging reliability and safety requirements are not realizable without effective means of non-destructive testing (NDT) that may be used to monitor the condition of reactor pressure vessel materials in order to guarantee safe operation of the tested structure. Another important objective is also to assess its remaining life or the need for a replacement, and to dramatically reduce direct and indirect costs such as those associated with plant outage. In this context, it is of crucial importance to be able to monitor the growth of defects such as cracks or corrosion, and to estimate their size as accurately as possible [4, 5]. The most appropriate NDT method for studying material deformation under fatigue loading is acoustic emission (AE) technology. It’s a useful tool for detection of leakage and after noise filtering also for detection of crack initiation and its growth under operation [6]. Most of the published work is directed to plastic deformation and initiation and propagation of cracks [7, 8].

Researchers also are trying to develop a new identification method for separation of signals into various types. For example, in [9] AE signals using the new identification method are divided into different types: the emitted by dislocations, by micro- and macrocracks. The base consists of a two-parameter distribution E_{AE} - K_r. E_{AE} is energy of AE signal and K_r is frequency coefficient defined as the sum of standard deviations of AE signals wavelet decomposition.
coefficients (shows the contribution of a frequency components in a signal). Based on the activity of various AE signals, six stages of fatigue were found. Based on k-means cluster algorithm in [10], different AE sources are classified into three clusters. The results indicate that the AE characteristics of different AE sources, such as plastic deformation, cracking and martensitic transformation, differ significantly, which could be of much help in analyzing and judging the fatigue situation.

Several researchers have been working in the area of low-cycle fatigue (LCF) (crack-growth rate $> 10^{-3}$ in./cycle). This paper will describe a research program in which AE was studied in high-cycle region. In comparison with LCF, stage of initiation of micro-cracks is in high-cycle region much more significant and can take several tens of percent of whole fatigue life. However, the detection and analysis of AE in high-cycle fatigue (HCF) presents some unique problems. The crack growth rate is relatively small and, thus, the level of AE is low compared to the more common tests. Thus, background and extraneous-noise rejection becomes extremely important. The problem is complicated by the fact that the fatigue loading system itself can produce extraneous noise. This noise may come from such sources as hydraulics and other load train slippage and abrasion [11]. Especially under HCF conditions more than 90% of lifetime is spent before cracks are usually detectable. The reason for this are small and subsurface cracks generated from fatigue induced compressive stresses within the surface region. Under HCF conditions very small non-detectable cracks can become unstable and result in catastrophic failure [12].

However, there are other important aspects of AE measurements, which are based on qualitative parameters of the received signals. The waveform shape depends on the cracking mode, enabling the classification of cracks in different materials. Shear cracks generally follow tensile as the material approaches to final failure. Therefore, crack characterization may lead to an early warning. In general, when a tensile event is occurring, the sides of the cracks move away from each other, leading to a transient volumetric change of the material and consequently most of the energy is transmitted in the form of longitudinal waves, while only a small amount in shear waves which propagate on a lower velocity [13]. Therefore, most of the energy is recorded quite early within the received waveform.

Among all AE parameters including amplitude, energy and frequency parameters, a number of emission events and ringdown counts was considered by [14] as the most direct reflection of microstructural variation in materials. Thus the count number is generally assumed to be proportional to the number of active microscopic events such as mobile dislocations, fractured inclusions and second phase particles, as well as twinning. Recently the shape of the initial part of the waveform is examined by the RA value which is defined as the rise time over the amplitude and is measured in $\mu$s/V (or ms/V), as suggested by relevant recommendations [15]. In the present study, an advanced IPL system, supplied by DAKEL Company, was used to investigate the evolution of early fatigue damage in 15Ch2NMFA low-alloyed steel of smooth-specimen fatigue under cyclic bending loading. The work is also focused on the analysis of the AE signal using identification methods for separation of signals into various types during load increasing phase (crack opening) and decreasing phase (crack closure).

2. Experimental procedure

2.1 Materials and mechanical testing

The material used in this study is a nuclear Cr–Ni–Mo–V low-alloyed steel, known as GOST 15Ch2NMFA. The smooth test specimens shown in Fig. 1a, were manufactured from the large compact tension (CT50) specimens which were taken from the forged ring of the reactor pressure vessel. Microstructure of the studied material due to heat treatment used (two-stage
quenching with subsequent tempering) is a mixture of heterogeneous bainite and martensite (see Fig. 1b). The minimum diameter and radius of curvature at the center part of the fatigue specimen were 10 mm and 35 mm, respectively. To minimize the effects of the surface irregularities on the fatigue lives, a final surface preparation is achieved, consisting of a polishing after emery and buffing polishing.

The bending fatigue tests were conducted on the electro-resonance RUMUL Cracktronic 8204/160 testing machine in high-cycle region at different stress amplitude levels ranging from 407 to 590 MPa, in laboratory air and at room temperature. The fatigue cycle was sinusoidal with a frequency about 113 Hz and the stress ratio was set to $R = -1$. Specimens were generally fatigued until failure unless otherwise specified.

2.2 Acoustic emission testing procedure

AE was monitored using an advanced IPL data acquisition system with a total system gain of 80 dB, supplied by DAKEL Company. Two piezoelectric sensors (DAKEL, type: MIDI – DAK 432 piezoceramic, sensing face material: stainless steel) were fixed on each end of the specimen by Loctite glue (see Fig. 2). The four-channel continuous measurement system IPL covers the frequency bandwidth of approximately 20 – 800 kHz with sampling rate of 2 MHz and ADC resolution of 12-bits (measuring range was also ± 2048 ADC). Data were collected, stored and analysed using DAKEL software - DAKEL-UI. The level of stress amplitude as a function of time were also recorded using the same data acquisition system (fifth channel of IPL system). The average AE wave velocity (4.8 mm/μs) was determined before tests by means of Pen-test (Hsu-Nielsen source). This average AE wave velocity was used for the determination of AE sources location generated at reduced-part of the specimen in each test.
Results include analysis of the number of acoustic waves (AE events), count rate, amplitude, duration and RA parameter over time during load increasing / decreasing phase and linear source location.

3. Results of acoustic emission response during fatigue

The AE behaviour was very similar at all stress amplitude levels and was characterized by three common features corresponding to different stages of fatigue damage. Figure 3 shows the most typical graphs of AE hit accumulation (black line) and count rate (various colors) at two stress levels, separated on types of sources. Large numbers of counts are emitted in the first period of fatigue life due to the movement and interaction of dislocations and persistent slip band formation - “area A”. The crack nucleation stage is characterized by low activity of AE signal with occasional peaks, and then, AE activity emitted by the growth and coalescence of the microcrack is increased – “area B”. At near-fracture period, sharp increase of AE activity is observed due to the macrocrack growth - “area C”.

![Fig. 3](image)

**Fig. 3** Time history of AE hit accumulation, count rate and loading frequency during fatigue test to failure

High activity of each type’s of AE sources is not constant during all time of fatigue test. A course of loading (resonant) frequency changes for the tested specimen taken with RUMUL fatigue machine was useful to identify the beginning of the macrocrack growth (blue points). This moment is shown in Fig. 3 from about 75th min, and 170th min, respectively.

The nucleation stage was also signaled by the sudden increase of the amplitude and rise time above zero stress. After the initiation, there was an intense AE bands with a clear boundary above zero stress (see Fig. 4). AE signals in this band may be caused by crack-face grinding while the crack was closed.

![Fig. 4](image)

**Fig. 4** Time history of hit amplitude (a) and rise time (b) depending on the stress amplitude (load)
A colorful distribution of load phases (see Fig. 5a) was proposed to study the AE behaviour during load increasing phase (crack opening) and decreasing phase (crack closure). The increasing phase is always marked in red and decreasing phase in blue line in the graphs. Most of the AE signals are generated at load decreasing phase, especially near zero load and less signals are generated during increasing load phase. It was found that at all stress levels, sharp increase of AE events at increase phase is observed, and it may become a warning signal of impending fatigue failure (in Fig. 3 at 80th min. and 200th min. respectively). The AE hits generated at decreasing phase are mostly constant before final fracture. However, the changes at increasing phase are also observed during nucleation stage (see Fig. 3a and 5b, marked with an arrow).

![Fig. 5](image)

**Fig. 5** Definition and colorful distribution of the load phases (a) and cumulative AE hits at increasing and decreasing phase under 520 MPa (b)

However, the qualitative parameters of AE show a very distinct and clear trend. Therefore, in order to understand the AE generated in all stages (areas), AE amplitude and duration distribution analysis has been performed. For these distribution analysis, AE signals generated at increasing / decreasing phase up to final fracture were used at all stress levels. The most typical graphs are shown in Fig. 6. As can be seen the decrease phase amplitude has the highest frequency of occurrence at about 59 and 66 dB\textsubscript{AE}, and at increasing phase of 58 and 64 dB\textsubscript{AE}, respectively. The more significant differences are in the stages of fatigue. Low amplitudes about 58 dB\textsubscript{AE} coming from the stage of nucleation and growth of the microcracks – “area B+C” while the higher amplitudes about 64 dB\textsubscript{AE} are emitted by the movement and interaction of dislocations and slip band formation in the first period of fatigue life – “area A”. The peaks amplitude detected may point to different mechanisms of fatigue damage.

![Fig. 6](image)

**Fig. 6** AE amplitude histogram at increasing / decreasing phase (a) and in different stages of fatigue damage
Figure 7 again shows duration distribution diagram. In this case, the frequency of occurrence peaks also occur due to microstructure changes at two duration levels. The very short duration (< 5 \( \mu \)s) occur most frequently during load increasing phase and in the last half of fatigue loading (growth and propagation of crack) while the duration about 80 \( \mu \)s occur both at increasing phase (secondarily) and during the first period of the movement and interaction of dislocations and slip band formation. A typical example of the AE hits generated in the “area A” and “area B” is seen in Fig. 8.

![Fig. 7 AE duration histogram at increasing / decreasing phase (a) and in different stages of fatigue damage](image)

Relationship between the AE amplitude values and duration at both load phases and in different stages of fatigue process is given in Fig. 9. It is evident that AE signals with amplitudes from 54 to 61 dB\(_{AE}\) and duration from zero to 100 \( \mu \)s are clearly demarcated from the signals coming from the (macro)crack propagation (“area C”), and decreasing phase, respectively.

![Fig. 9 Relationship between amplitude vs. duration in different stages (a) and at increasing/decreasing phase (b)](image)
RA value and average frequency of the AE signals generated during fatigue tests (up to final fracture) have been determined based on code [15]. Higher RA value is an indication that shear cracks dominate the fatigue process. Relationship between the RA values and average frequencies of tested specimen is given in Fig. 10. It is observed the same crack types occur at each stress level and in different stages of fatigue process, as illustrated by Fig. 11. However, the tensile cracks are found more dominant in “area A”.

**Fig. 10** Example of relationship between RA value and average frequency of fatigued specimen (a) in different stages and (b) at load decreasing / increasing phase

**Fig. 11** Fatigue fracture surface of 15Ch2NMFA steel ($\sigma_a = 586$ MPa, $N_f = 81.1 \times 10^5$ cycles)

4. Conclusion

One objective of this research was to investigate the possibility of selection stages of the fatigue damage accumulation and to propose a methodology for the assessment of the early manifestations of fatigue loading in power plant material. The fatigue process has been best described using AE data by the plot of count rate and cumulative AE hit versus time (cycles) to failure as shown in Fig. 3. The AE signal initially shows an increase due to the movement and interaction of dislocations and persistent slip band formation (“area A”), followed by steady state growth where the crack is nucleated (“area B”), and then finally growth and coalescence of the microcracks to the size of macrocrack (“area C”). The microcracks nucleation and their growth is accompanied by a low activity in count rate and cumulative AE hit and it seems difficult to detect the initiation of microcracks (see Fig 9). However, the AE parameters analysis (such as the duration, amplitude) has shown a very distinct and clear trend. In particular, it was found that at all stress levels, sharp increase of AE hits at load increase phase is observed, and it can be used as an indicator of nucleation and growth of microcrack (see Fig. 5b, 9b). It was concluded that AE parameters are sensitive to the damage process (apart from the total activity) and should be further studied in order to lead to early warning against final fracture.
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References