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Use of acoustic emission method for identification of fatigue micro-cracks creation

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Abstract

This paper is a contribution to the discussion on the possibilities of identification of the time behaviour of various stages of fatigue lifetime directly during experiments using non-destructive testing methods (mainly acoustic emission method). We focus especially on detection and characterization of the transition from the stage of cycling damage accumulation to micro-cracks creation. In the past years, the laboratory of fatigue properties of FME received and published plenty of information about propagation of damage mainly in Al and Ti alloys. In this paper are presented and compared the results of new experiments with steel used for nuclear reactors and Inconel alloy. This work is focused on comparison of selected parameters of acoustic emission signal in pre-initiation and initiation stage of fatigue crack creation. Acoustic emission hits with higher stress were detected in the pre-initiation stage whereas the initiation stage hits exhibited low stress.

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Keywords: *high cycle fatigue, crack, acoustic emission, signal processing, steel for nuclear reactor, Inconel*

1. Introduction

1.1. Fatigue

Efforts to increase the lifetime and efficiency of technical units puts high demands on the selected materials and their processing, especially in the transport and energy sectors, particularly with regard to their long term properties.

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Knowledge of the technical state of construction material to be used in the production of such transport equipment or high-energy piping systems is as important as having enough information about the material in terms of stress characteristics, resistance to high temperature corrosion resistance or as fatigue crack propagation. Therefore, it is still extremely important to deepen understanding of the mechanical properties and degradation processes of materials, particularly in the case of fatigue loading

The fatigue damage is usually divided into some basic stages. There are many different ways of detailed evaluation of fatigue process stages. For our purposes it is sufficient the basic division shown in Figure 1. It is the dislocation structure that passes changes featured by cyclic material hardening/softening at the beginning of the cyclic charging. During the next period, no material changes appear visually, however new processes provoked by continuous charging proceed inside the structure. This period is usually designated as the period of damage accumulation. At the end of this period, the damage becomes localized in the suitable (predisposed) sites. Micro cracks appear and some of them start to join producing short cracks and finally the main crack creates. The biggest attention is paid to the description of crack initiation at this time. As to the material property evaluation it is, however, quite important to follow the processes imminently preceding the appearance of the fatigue crack. These changes take place at the micro-structural level and the current methods are able to identify them only with great difficulties.

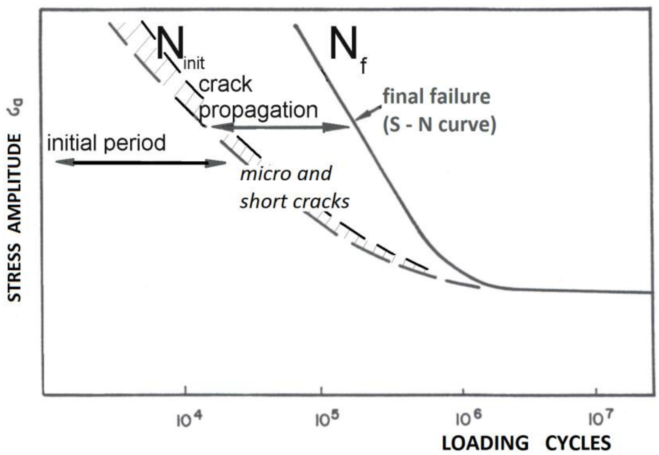


Fig.1. Example of S-N dependence with indicated basic stages of cracks creation and propagation

1.2. Acoustic emission

NDT methods, especially acoustic emission (AE), are applied very significantly in condition monitoring of many engineering structures. The acoustic emission as a phenomenon can be defined as transient elastic waves resulting from local internal micro-displacements in materials of the tested structures. AE method has become a common NDT method used mainly for testing of stationary equipment - tanks, pressure vessels, reactors, pipelines, bridges, etc. In these applications, the AE method is fully accepted and standardized. AE gives much information about materials response to applied stress. It is useful for the detection and identification of growing defects in material. Thanks to its sensitivity it can detect such processes as micro-crack formation and growth, movement of dislocation group, fracture, slip or debonding of precipitates [1, 2]. The primary sources of AE in metals are the processes of plastic deformation and crack growth, which are discrete energy release mechanisms on a crystalline microstructure scale.

The advantage of AE method is the ability of testing of the entire structure, localization of potential defects and assessment of their risk for the integrity of the structure. AE application brings significant economic benefit to all users. A partial disadvantage is the limited ability of precise identification of the defect type, so that it is necessary to use other NDT methods for their identification.

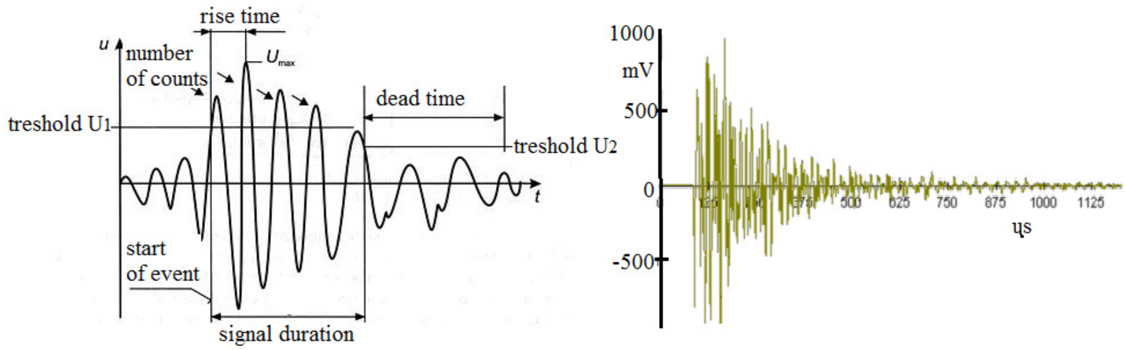


Fig. 2 Schema of main parameters of AE burst (left) and example of real burst signal from a sensor (right).

2. Experimental equipment and used materials

2.1. Fatigue tests

The fatigue tests have been realised with the resonant testing device RUMUL Cracktronic 8204/160 working on the principle of electromagnetic resonance and loading the specimen with four point symmetric bending (R = -1) and partially with fluctuating stress (app. R = 0,12). The resonance frequency of the mentioned specimens moved around 80 - 120 Hz (depending on the toughness of the used material). The dynamic bending moment in electro-resonant testing machines is generated by means of an electromagnetic driven resonator. The tested specimen itself is part of the spring/mass system and influences with its stiffness the resonant frequency of the machine. In case that the rigidity of the tested sample is changed (cyclic hardening or softening in the initial part of loading, fatigue crack initiation and crack spreading etc.) this frequency is changed. It means that it is possible to estimate approximately the length of these stages. From practical point of view the most important is the identification of the fatigue crack spreading phase of course, but in case of detailed analysis some changes of frequency can be detected in the stage of "stable" mode.

The main disadvantage of these testing equipments is the limited amount of information about the actual process of cycling degradation. Determining the period from appearing of fatigue crack to final failure of the sample, eventually finding the instant of micro-crack appearance or interconnection, is also very important. For example mutual comparison of the length of crack propagation stage to final fracture is one of the criteria that can decide the suitability of the material for the construction of given device in practice – mainly in the area of transport industry (see also Fig.1).

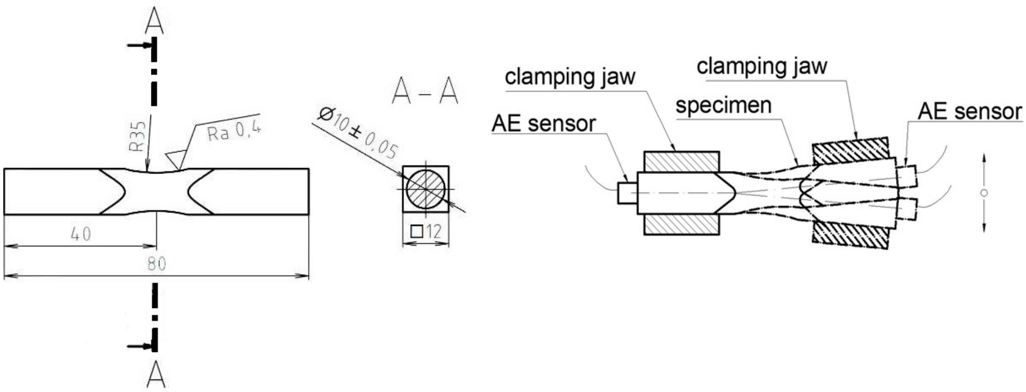


Fig. 3 Shape of specimen, scheme of used loading and basic placement of AE sensors

2.2. Materials

The results presented in this article were obtained primarily on Cr–Ni–Mo–V ferrite low-alloy steel 15Ch2NMFA known as GOST 15Ch(Kh)2NMFA, whose chemical composition and mechanical properties are shown in Tables 1 and 2 respectively. Ferrite low-alloy steel is used for VVER pressure vessels, which are one of the most important parts of power reactor. [3, 4]

Part of the results was achieved on the material Inconel 713LC - low carbon variant of nickel-based alloy Inconel 713, which belongs to a group of so-called super alloys. These alloys are appropriate for applications in high temperatures, high stresses or in corrosive environment. Structure of nickel-based alloys usually consists of the solid solution austenite with dispersoid or precipitate particles therefore there is possibility of solution hardening. Hardening effect is provided by blocking of dislocation movement. Majority of applications involves corrosion resistance and/or heat resistance – aircraft, chemical and petrochemical industry, energetic, metal processing, automotive etc.

Table 1. Chemical composition of 15Ch2NMFA steel

Material	Element (wt %)							
	C	Mn	Si	P	S	Cr	Ni	Mo
15CH2NMFA	0,15	0,50	0,23	max 0,02	max 0,02	2,1	1,1	0,60

Table 2. Mechanical properties of 15Ch2NMFA steel

Material	E (GPa	Rp0,2 (MPa)	Rm (MPa)	A (%)	Z (%)
15Ch2NMFA	208	540	639	22	76,5

2.3. AE measurement

AE signal was detected by a DAKEL-XEDO monitoring system with a total system gain of 80 dB. Two piezoelectric sensors (DAKEL, type: MIDI) were clamped on each end of the specimen by Loctite glue to constitute a two-channel location system shown in Fig. 3. Results include linear source location, analysis of the number of AE events, count rate and RMS.

Fig. 4 Dakel AE monitoring system – XEDO (8 +1 channels) and IPL (4 + 1 channel).

The part of newest measurements was monitored using an advanced IPL data acquisition (Fig. 4). 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 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.

All measurements have been completed with noticed resonance frequency changes of the tested sample coming from the fatigue load apparatus RUMUL CRACKTRONIC.

3. Overview of experimental results

3.1. Basic treatment of AE signal - counts rate vs. time history

The change of AE activity roughly corresponds to the change of loading frequency (Fig. 4). Classical techniques of optical observation of surface do not provide any obvious reason for this phenomenon. On the basis of analogy with other observations it is possible to expect that the reason of emission activity can be for example accumulation of energy sufficient for loosening of dislocations captured in structural obstacles, occurrence of micro-cracks and eventual connecting of existing micro-cracks. The reason of increased emission activity during the so called stable mode can be also the changes of material substructure – emphasizing of sub-seeds, mutual rotation of suitable areas in frame of individual seeds of material etc. can appear [5, 6].

Fig. 5 depicts an example of record of oversight count over predefined threshold of AE signal, which corresponds to record of frequency curve change. It can be clearly seen that changes of AE signal correspond very closely to changes in loading frequency, and so the AE signal confirms the existence of structural changes during the period of damage cumulating (Ind. II). Very obvious is the rise of AE activity in consequence of main fatigue crack propagation (Ind. III) and also in the initial stage of cyclic hardening (Ind. I).

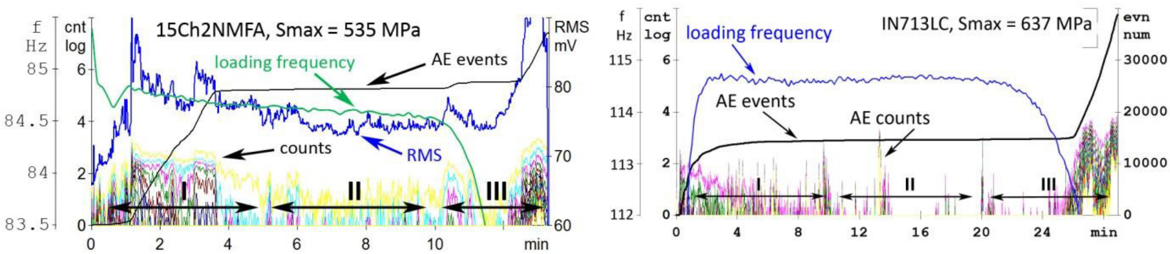


Fig. 5 Comparison of AE signals accumulation (count rate – cnt [log], AE events – evn [num]) and loading frequency (f [Hz]) during short fatigue test of 15Ch2NMFA and Inconel 713LC a) $\sigma_a = 535$ MPa, $N_f = 92,5 \times 10^3$ cycles; b) $\sigma_a = 637$ MPa, $N_f = 1,98 \times 10^5$ cycles.

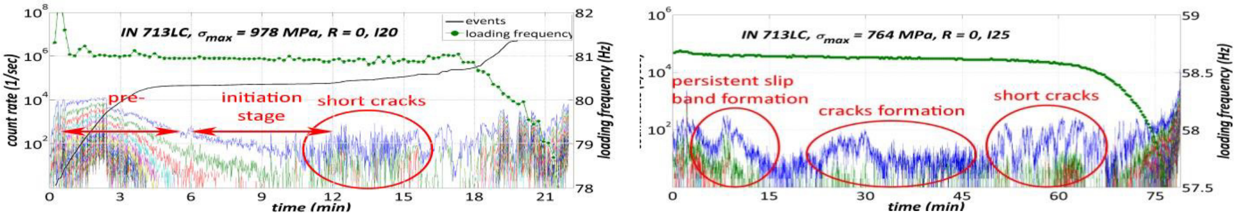


Fig. 6 Examples of time history of counts rate and loading frequency - Inconel 713LC, $\sigma_{max} = 978$ MPa, $N_f = 1,05.10^5$ cycles (left) and 764 MPa, $N_f = 2,8 . 10^5$ cycles, fluctuating stress loading (app. R = 0,12).

According to signal classification by type of source it was found, that the formation of micro-cracks and its growth to the macro-crack size is characterized by an increase in count of AE signals [6]. In study of [7] was found, that clack closure phenomena is accompanied by high AE count values. AE signal has three regions which correspond to crack incubation stage, crack initiation stage and crack propagation stage.

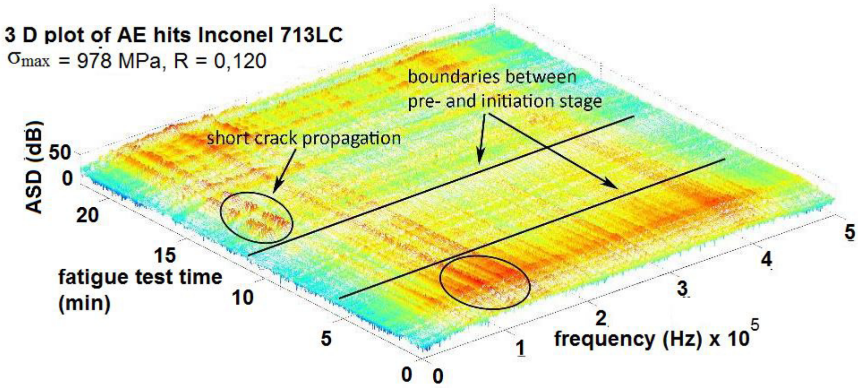


Fig. 7 Frequency spectrum evolution (3D plot) in the whole test from fig. 5 (left).

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 8 shows the most typical graphs of AE hit accumulation (black line) and count rate (various colours) 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 micro-crack is increased – “area B”. At near-fracture period, sharp increase of AE activity is observed due to the macro-crack growth - “area C”.

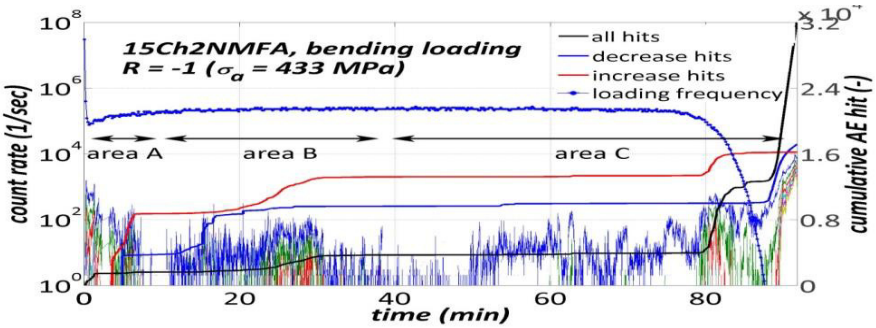


Fig.8 Long test of steel 15Ch2NMFA (N_f app. 5.10^5 cycles) with basic areas of the cyclic damage.

3.2 Use of AE source localization

It was very important to identify the location of relevant AE sources to eliminate noise sources (friction, test machine). Two AE sensors were used for linear source location. Linear source location and location distribution histogram was used for more accurate results (see Fig. 9).

In Fig. 10 are shown AE sources over the entire specimen volume and only at the notch. AE sources in red encircled area are connected with dislocation movement and slip formation of the stage I. There were found significant changes in the amplitude and frequency spectrum of the waveforms (a low amplitude was typical for AE hits) [8].

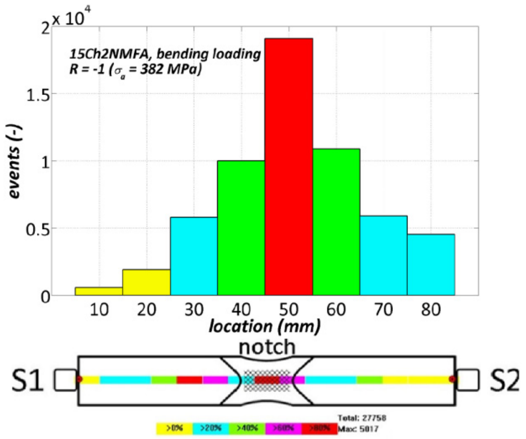


Fig. 9 Location of AE signal sources on the surface of specimen and number of localised events.

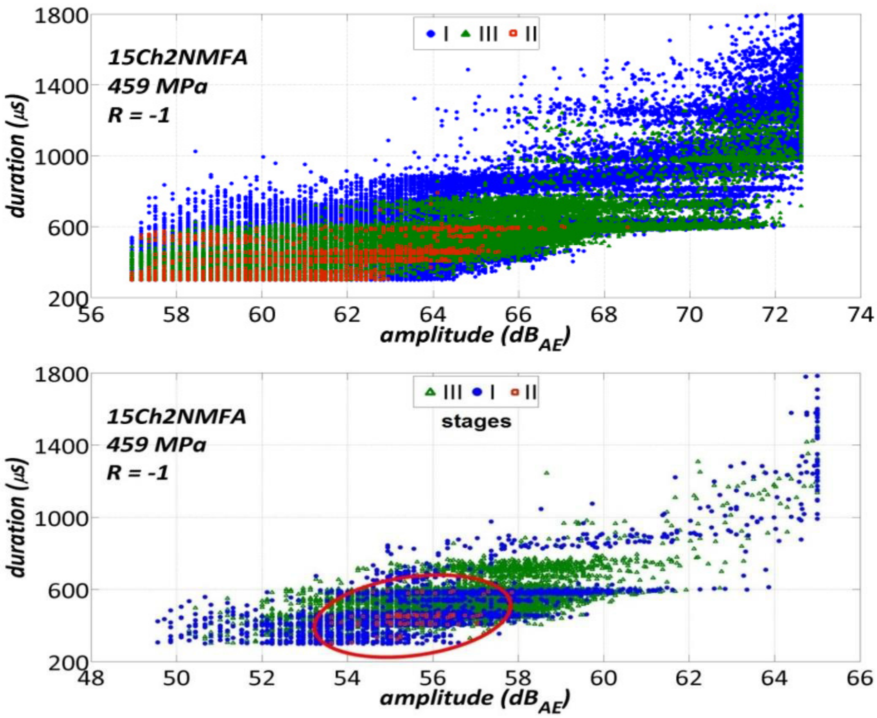


Fig. 10 AE source localization: a) all registered sources, b) only at the area of notch [8].

3.3 Other treatment of signal

Due to the fast sampling of AE signal it is possible to not only localize the signal sources, but it is also possible to distinguish the formation of sources at different stages of the cyclic load process. As a result of various processes the event parameters differ from the loading and relieving phase.

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. 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.

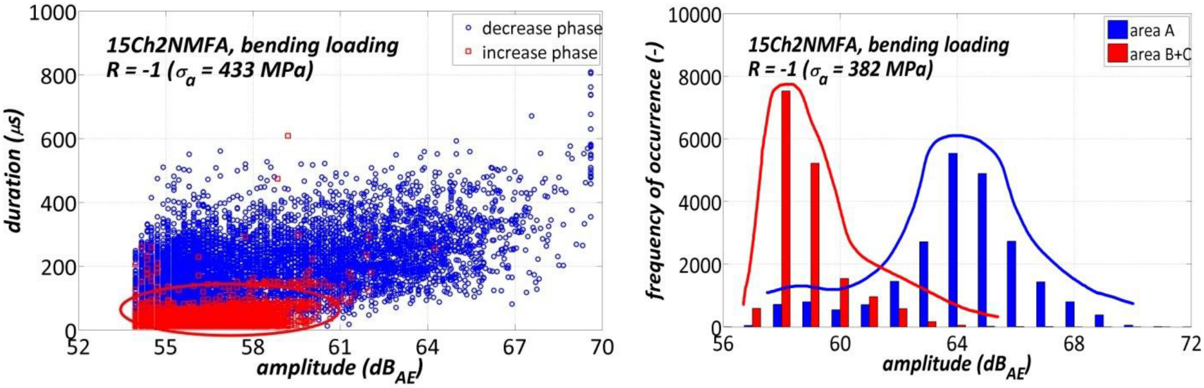
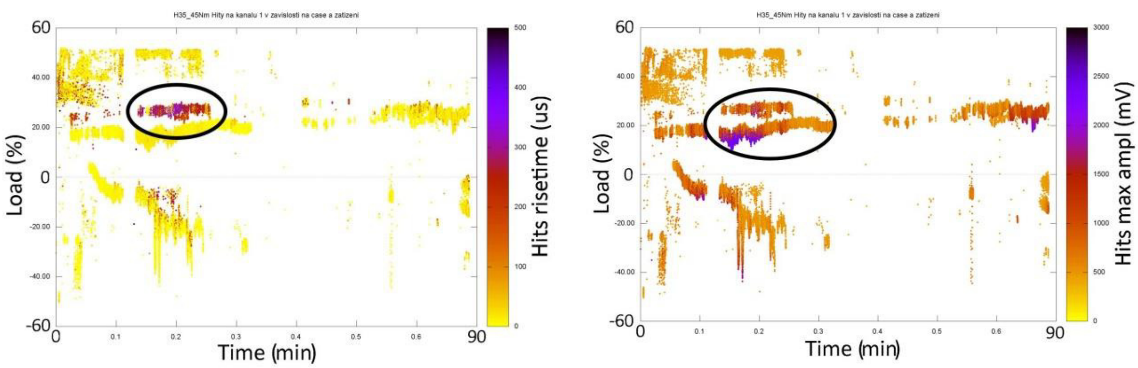


Fig. 11 AE duration and frequency occurrence histograms at increasing / decreasing phase and in different stages of fatigue damage [9].

High activity of each type's of AE sources is not constant during all time of fatigue test. The nucleation stage was also signalled 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. 12). AE signals in this band may be caused by crack-face grinding while the crack was closed.



a) b)

Fig.12 Time history of hit amplitude (a) and rise time (b) depending on the stress amplitude (load).

4. Conclusion

Fatigue evaluation of 15Ch2NMFA steel and Inconel 713LC using AE method was presented. These studies build on our previous large-scale studies carried on Al, Mg and Ti alloys [11]. AE gives much information about materials response to cyclic loading. 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. All records have three similar features which correspond to stages of the fatigue process. 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 micro-cracks to the size of macro-crack ("area C"). The micro-cracks nucleation and their growth are accompanied by a low activity in count rate and cumulative AE hit and it seems difficult to detect the initiation of micro-cracks. 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 micro-crack. It was concluded that AE parameters are sensitive to the damage process (apart from the total activity). Therefore, it can be concluded that the AE technique can serve as a sensitive early warning method for detecting fatigue damage in early stages of fatigue process and should be further studied in order to lead to early warning against final fracture.

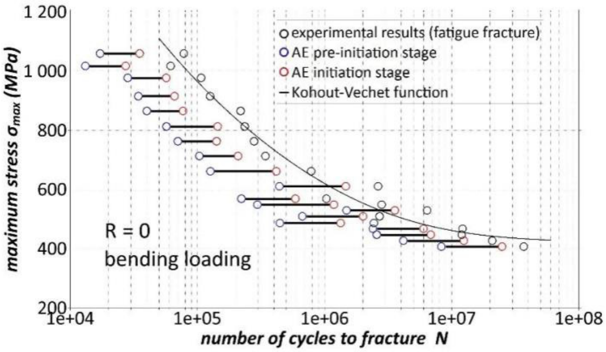


Fig. 12 Example of the practical results of the identification process stages of pre-initiation and initial propagation of fatigue cracks for tool steel with AE method.

The fact that every measuring is unique is still a great problem for repeatable application of AE method. This is caused by very difficult ensuring absolutely identical conditions of every measuring (often long-lasting). Before all, various materials differ significantly in their "acoustic activity" and its character. The possibility of mutual comparison of results strongly depends on used sensors, on the way they are fastened to the sample, on the contact medium between the surface of the material and the sensor, etc. The shape of the samples and the distance between the sensor and the place of monitored defect play an important role, too.

Beyond these restrictive factors, the method of acoustic emission has its indisputable justification for the identification of fatigue degradation stage. It is necessary to work out standard procedures, including rules for setting parameters of AE analyser, location of sensors, and, of course, the way of evaluation of acquired signal. Extensive experimental work is necessary to work out general procedures of evaluation. Searching for congenial parameters and their fitting into the evaluation programmes will require considerable effort. AE method can further enrich knowledge about individual stages of fatigue damage. It is however not possible to expect from AE method the exact identification of AE sources. That is possible only by connecting AE with further laboratory procedures capable of identification of processes in material substructure (e.g. with X-ray diffraction analysis) [12]. These commonly gained experiences will contribute to identification of processes, which take place in materials even in loads which correspond to very high lifetimes and which are very difficult to identify by common material testing procedures.

For qualified estimate of real sources of acoustic emission in material, it is necessary to make use of much more demanding signal processing, using suitable mathematics methods. It is necessary to take off characteristic shapes of events in individual stages of damage and to provide detailed frequency analysis.

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