Identification of Acoustic Emission Sources in Early Stages of Fatigue Process of Inconel 713LC

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Abstract. Inconel 713LC is low carbon variant of Inconel 713 nickel-based cast alloy. The biggest advantage of these alloys is their ability to resist a wide variety of operating conditions (corrosive environment, high temperature, high stresses). Main area of applications is aircraft, energetic, chemical and petrochemical industry etc. In many applications, components undergo cyclic stresses. This study presents results of acoustic emission response of Inconel 713LC during high-cycle fatigue testing. In comparison with low-cycle fatigue, 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. This work is focused on comparison of selected parameters of acoustic emission signal in pre-initiation and initiation stage of fatigue crack creation. Signal data were specified by linear location technique, hence only signal from shallow notch was analysed. Acoustic emission signal was correlated with frequency of load reversals which is a function of specimen's rigidity (modulus). Acoustic emission hits with higher stress were detected in pre-initiation stage whereas initiation stage hits exhibited low stress. Acoustic emission signal measurements are supplemented by fractographic and metallographic analysis.

Introduction

Inconel 713LC belongs to group of so-called nickel superalloys, which are useful for critical applications (corrosive environment, high temperature, high stresses or combination of these factors). Superalloys can be used at temperatures above 540 °C. This high-temperature stability is due to the precipitation of γ' – $Ni_3(Al,Ti)$ phase. Example of usage are aero engines, turbo blowers, parts of gas turbines and other applications where high strength steels or surface modified steels are insufficient [1].

Components made of Inconel 713LC are subjected to both high-cycle fatigue (HCF) and low-cycle fatigue (LCF) very often. For components such as turbine blades, rupture is frequently caused by purely mechanical fatigue complemented with thermal fluctuations and large stress gradient. Data on the fatigue properties of nickel-based alloys are still quite limited even thought experimental data are necessary for establishment of criteria for design and maintenance of machines [2].

Previous studies on Inconel 713 LC were focused on analysis of tensile fatigue at high temperature [3, 4]. The influence of protective diffusion aluminide coatings on fatigue properties was investigated by Slamecka et al [5]. Differences between the fatigue life of coated and uncoated specimens weren't significant.

A method of detecting early stages of fatigue could provide the basis of a testing technique for predicting fatigue life. Some non-destructive evaluation techniques, such as ultrasonic and acoustic emission (AE), have been used to monitor the fatigue damage. Moreover, AE is useful tool for continuous state monitoring, which is very important to observe current safety and reliability requirements [6]. This method gives new supplementary information collection about materials response to applied stress, which is closely related to strength, damage, and failure [7].

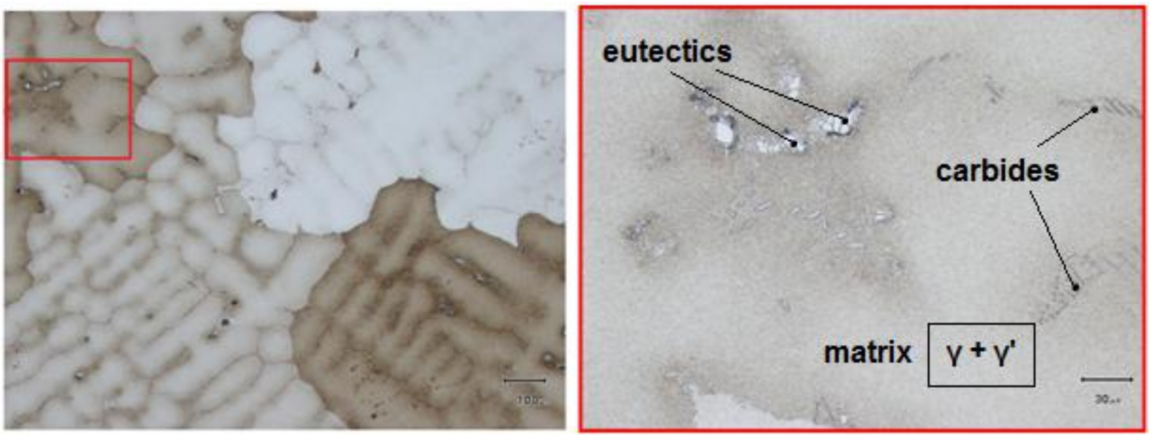
AE events in metals during fatigue loading are caused by movements and multiplication of dislocations, slip, fracture and debonding of precipitates or microcrack formation and growth [8]. Fatigue damage characteristics of structural materials using AE technique has been investigated by several researchers used signal classification technique (by type of sources - microcracks, dislocations) to identify the stages of bending fatigue [9]. One of conclusions from this measurement is that the formation of microcracks and their development (to the size of macrocracks) is accompanied by an increase in count of AE signals. In the work of [10] was found that crack initiation is indicated by rapid increase of AE count values at positive peak stress. Furthermore high AE count values around zero stress characterize crack closure phenomena. AE signal activity regions corresponded with three basic fatigue stages - crack incubation stage, and crack initiation stage and propagation stage. It's very useful for understanding the microphenomena that happen in the material before crack nucleation.

The main aim of this paper is to propose a methodology to evaluate early manifestations of fatigue damage under bending loading and to describe the evolution of fatigue crack by AE parameters then.

1. Experimental procedure

1.1 Material and microstructure

Chemical compositions of Inconel 713LC (wt %) is 11.98 Cr, 6.04 Al, 4.01 Mo, 1.82 Nb, 0.59 Ti, 0.06 Zr, 0.06 C, 0.008 B (other and undesirable elements are in acceptable ranges). Conventionally cast cylindrical rods were provided by the company PBS Velka Bites a. s. The structure of material is made up of coarse dendritic grains. The grain size determined by means of linear method was 2,9 mm.

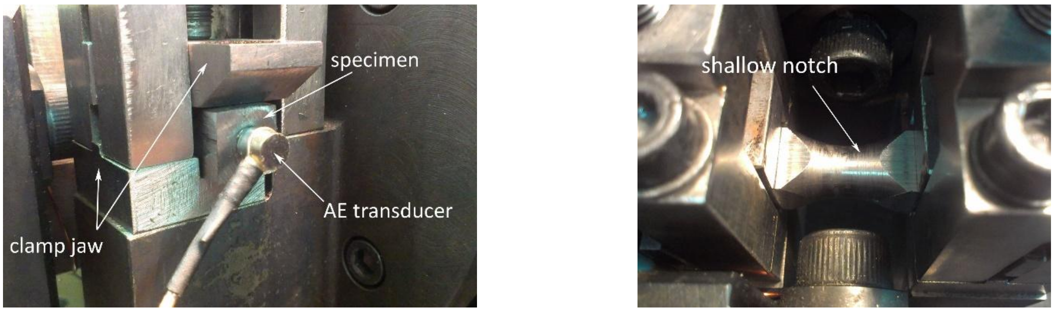


Pic. 1. Microstructure of Inconel 713LC

The microstructure consists of solid solution γ with fine hardening coherent precipitates γ' (Ni_3Al or $Ni_3(AlTi)$). Non-coherent carbides of Nb, Mo, Zr can be seen in interdendritic area and at grain boundaries in a form of 'Chinese characters'. Microstructure also shows typical casting defects - shrinkage porosity - distributed black points in Pic. 1. It is one of reasons why fatigue data of cast materials exhibit large scatter [3].

1.2 Mechanical testing

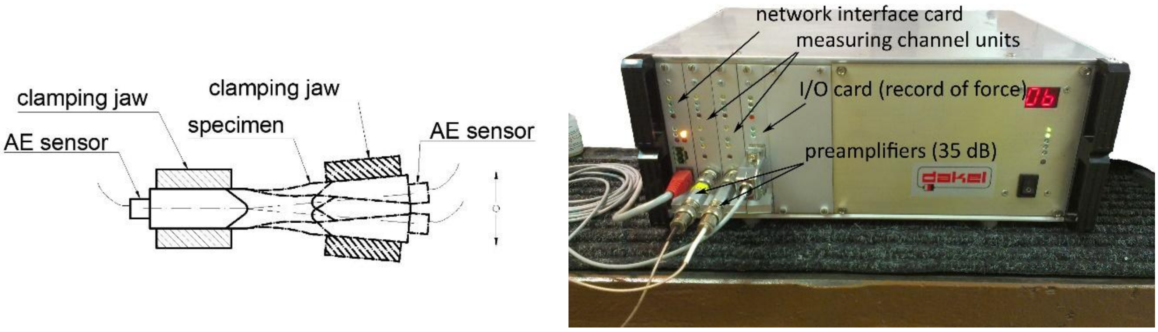
The bending fatigue tests were carried out on the electro-resonance RUMUL Cracktronic 8204/160 testing machine in high-cycle region at room temperature (see Pic. 2). The fatigue cycle was sinusoidal and the stress ratio was set to R = 0. The specimens were generally fatigued until failure.



Pic. 2. RUMUL Cracktronic 8204/160 with specimen and location of AE transducer

1.3 AE testing procedure

AE was detected by a DAKEL-XEDO monitoring system with a total system gain of 80 dB (see Pic. 3b). Two piezoelectric sensors (DAKEL, type: MIDI) were clamped on each end of the specimen by Loctite glue to constitute a two-channel linear location system shown in Pic. 3a. Results include linear source location, analysis of the number of acoustic waves (AE events), count rate and RMS. AE wave velocity (4800 m/s) was determined before tests by means of Pen-test.

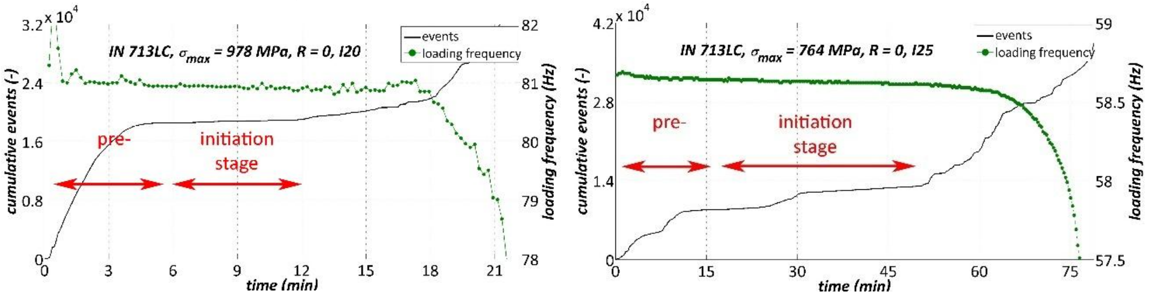


a) b)

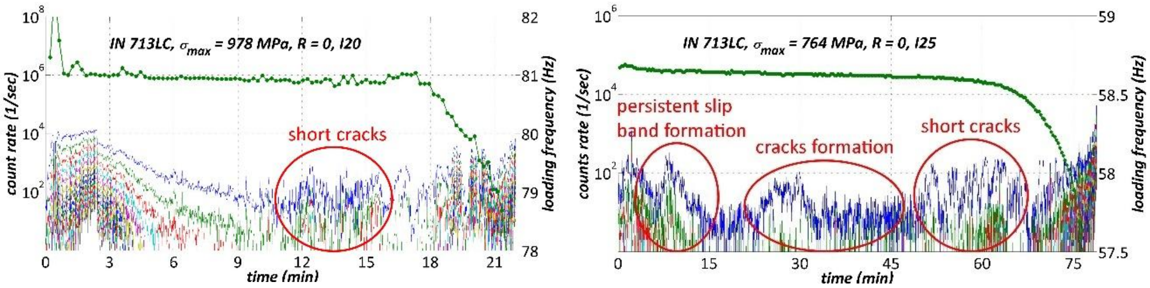
Pic. 3. Schematic illustration of specimen loading (a), diagnostic system AE: DAKEL-XEDO (b)

2. Acoustic emission response during fatigue loading

The AE measurement was carried out at different stress levels (from 488 to 1060 MPa). All measurements could be characterized by three common features. This is best illustrated cumulative events in Pic. 4. An increase represents pre-initiation stage (mechanical properties changes - movement and interaction of dislocations and persistent slip band formation). This is followed by the crack nucleation stage which is characterized by low activity of AE signal with occasional peaks. In our last work [11], AE signal response to main crack propagation was significantly delayed (by R = -1), whereas in this study AE provides early warnings of short crack propagation in the third period (in Pic. 5 marked with a red circle).



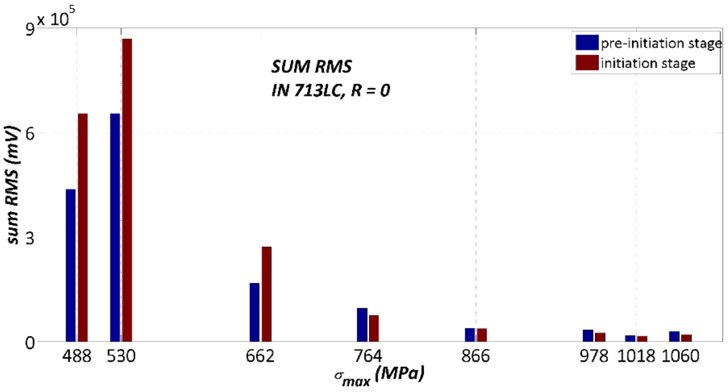
Pic. 4. Typical course of AE events and course of loading (resonant) frequency of the test machine



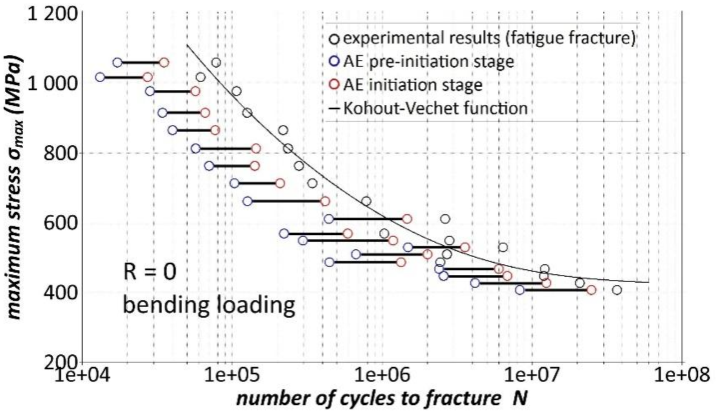
Pic. 5. Typical course of AE count rate and course of loading (resonant) frequency of the test machine

The RMS parameter was also investigated at all stress levels. In Picture 6 is shown a sum of RMS that actually represents the AE signal power (RMS over time) in pre- and initiation stage. From the graph is evident that a sum of RMS is greater in the initiation stage at the lower stress levels and it is decreasing from 764 MPa to higher stress levels.

Results confirm the assumption that the crack formation mechanism at lower stresses takes longer in comparison with higher stresses. This can be also seen in Pic. 7. The blue circles indicate the end of the pre-initiation stage and the red ones indicate the end of the initiation stage. It's also apparent, that a period between blue and red circles extend with decreasing stress level.

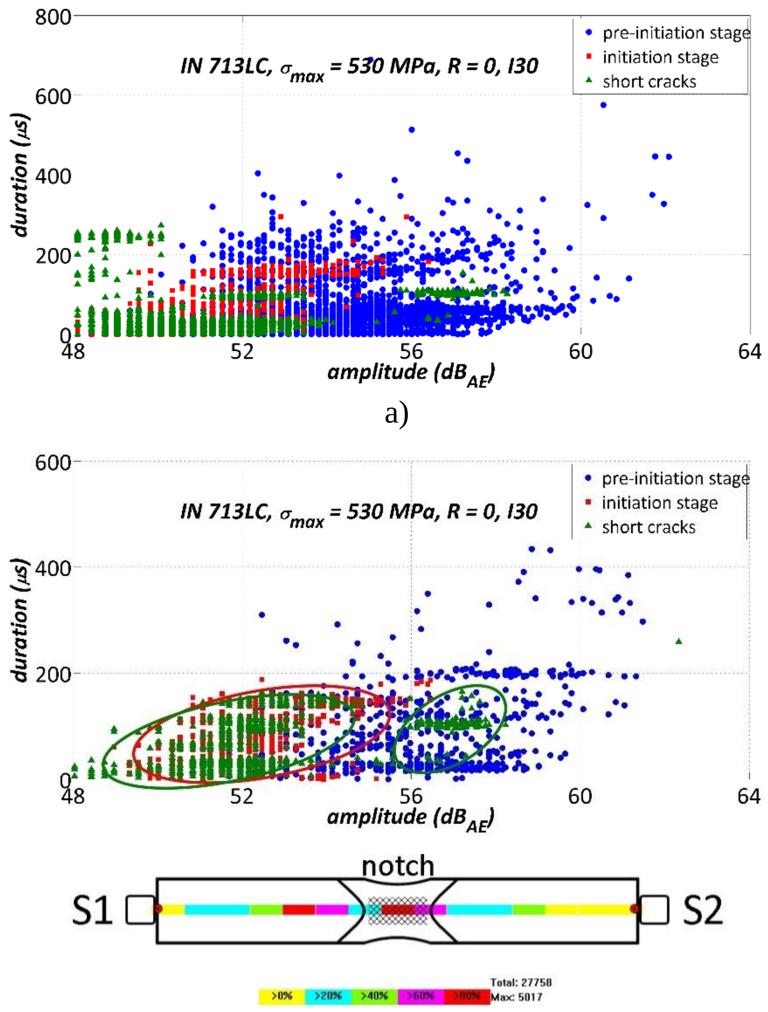


Pic. 6. Sum of RMS over time (AE signal power) in pre- and initiation stage at different stress levels



Pic. 7. S-N curve of Inconel 713LC at room temperature and approximate boundaries between AE pre-initiation and initiation stages

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. In Pic. 8. are the examples of amplitude vs. duration plots - from all sources in Pic. 8a, and only from the notch (using source location) in Pic. 8b.



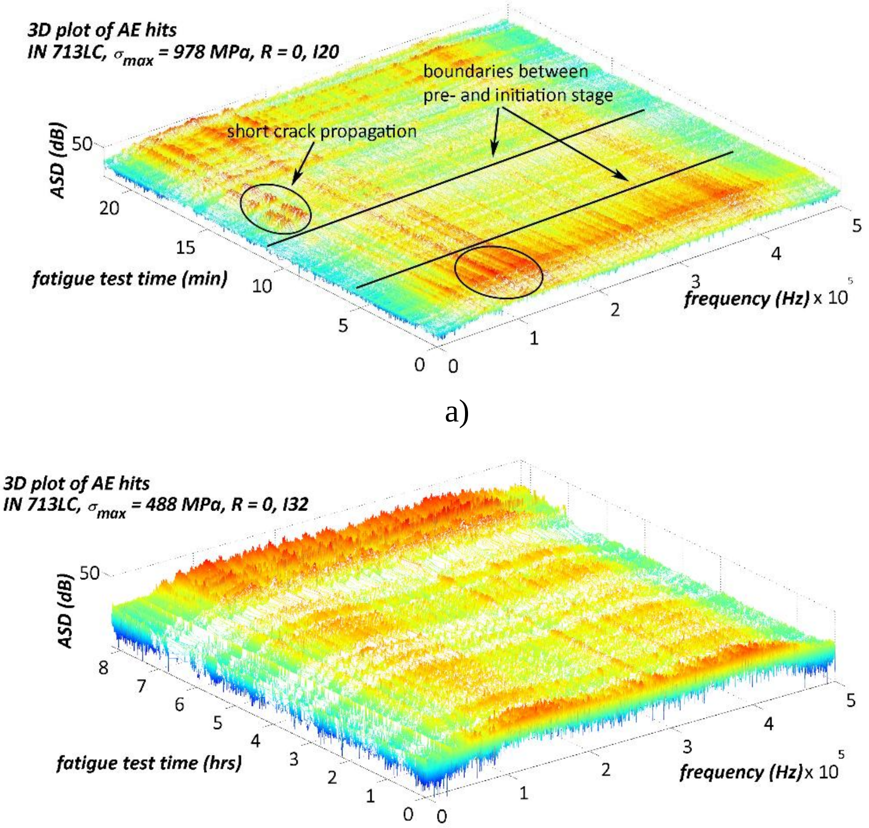
a)

b)

Pic. 8. Amplitude vs. duration plot in different stages of fatigue
a) all sources, b) sources only at the notch

It was found that blue points (in Pic. 8b) are probablyAE sources coming from the pre-initiation stage, i.e. sources from dislocation movements or slip plane formation with higher amplitudes (from 53 to 58 dB). The initiation stage is typical for low amplitudes (from 50 to 54 dB). These are marked in red encircled area in Pic. 8b.It is very difficult to distinguish between AE signals (AE hits) coming from microcracks formation and growth and signals coming from coalescence and propagation of (short) cracks. However, some differences in short cracks propagation stage have been found (green encircled areas).

There have been also found significant changes in the amplitude and frequency spectrum of the waveforms. It is actually a frequency spectrum evolution over test time and the third dimension (amplitude size) is a color scale (see Pic. 9). The largest part of the spectral density was transferred at 140 and 180 kHz. At the beginning, all frequency components were significant but they decreased from 200 to 300 kHz during the test time. The low frequencies (about 60 and 80 kHz - marked black ring) were typical for the short crack propagation stage.



a)

b)

Pic. 9. Amplitude spectral density during whole fatigue test
a) high stress level, b) low stress level

High-cycle bending fatigue assessment of Inconel 713LC, analysis of AE response of this material and analysis of loading (resonant) frequency changes of test machine at the beginning of main crack growth was presented.The results confirm utility of these non-destructive methods on the field of basic research of the fatigue processes in the material.The AE methods identified the changes in the material during pre- and initiation stages, namely the process of movement of dislocations, slip band formationand the fatigue crack nucleation and growth.

All measurements could be characterized by three common features which are shown in Pic. 4 and 5.Detailed information concerning the AE parameters such as duration, maximum amplitude or RMS and their changes during fatigue test have been discussed and can be also a good contribution to this research.Unfortunately, it is very difficult to distinguish between AE signals (AE hits) from each single stages.The loading frequency monitoring acquired by loading machine RUMUL Cracktronic have shown more complex information about the fatigue degradation of the material.

AE brings information on macroscopic volumes of analyzed material, which is a big advantage when investigating structurally heterogeneous processes that occur under cyclic loading. Further research will be extended to the electrical potential difference measurement and observation of surface microstructure for more accurate and detailed information about the pre- and initiation stages of the fatigue process.

Acknowledgements

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