ACOUSTIC EMISSION RESPONSE DURING HIGH-CYCLE FATIGUE LOADING OF INCONEL 713LC

Denisa BÁRTKOVÁ, František VLAŠIC, Pavel MAZAL, Ondřej DVOŘÁČEK

Brno University of Technology, Faculty of Mechanical Engineering, Brno, Czech Republic, EU,
bartkova@uk.fme.vutbr.cz

Abstract

This study presents results of high-cycle fatigue measurements of cast polycrystalline nickel superalloy Inconel 713LC and the analysis of acoustic emission response of this material. Inconel 713LC is usually used for gas turbines in aerospace and power industry. Fatigue is one of the most significant degradation mechanisms occurred in this application. Acoustic emission technique is an effective non-destructive method of detecting active structural defects or defects which could grow during service. It is also an adequate tool for monitoring a fatigue process. The particular aim of this study is to propose a methodology for evaluation of the early manifestations of fatigue damage and to describe the evolution of fatigue crack by acoustic emission parameters then. Smooth cylindrical specimens were subjected to alternating bending fatigue loading at room temperature. Two acoustic emission sensors were attached on the face of each specimen. Measured fatigue data were represented in a form of S-N curves. An examination of crack initiation sites and microstructure has been also performed.
Four stages in the fatigue life of specimen were distinguishable in measured acoustic emission signal energy. It was found that for first stage of fatigue life is typical signal with highest energy.

Keywords: Inconel, fatigue damage, acoustic emission, crack initiation

1. INTRODUCTION

Nickel-based alloys are so useful thanks to their ability to resist a wide variety of severe operating conditions - corrosive environment, high temperature, high stresses or combination of these factors. Inconel 713LC is low carbon variant of Inconel 713 and belongs to a group of so-called superalloys, which can be used at temperatures above 540 °C. This high-temperature stability is due to the precipitation of γ' - $Ni_3(Al,Ti)$ phase. Nickel makes solid solution with many alloying elements, therefore there is possibility of solution hardening. Aluminum and titanium have limited solubility in alloy, and their solubility decreases with decreasing temperature. Due to these facts, precipitates can be generated from a supersaturated solid solution during heat treatment [1]. Thanks to face-centred cubic matrix are nickel-based alloys free from ductile-to-brittle transition [2].

Previous studies on Inconel 713LC were concerned with analysis of tensile fatigue at a temperature of 800°C [3, 4]. Slamečka et al. investigated influence of protective diffusion aluminide coatings under bending, torsion and their combination. It was found, that differences between the fatigue life of coated and uncoated specimens weren't significant. But these coatings are useful to improve high temperature oxidation and corrosion resistance [5].

Majority of applications involves corrosion resistance and/or heat resistance - aircraft, chemical and petrochemical industry, energetics, metal processing, automotive etc. Moreover, the current challenging reliability and safety requirements are not realizable without effective means of non-destructive testing (NDT) and continuous state monitoring [6].

Information-based fatigue damage monitoring using different sensors (e.g., acoustic emission, eddy currents and ultrasonic) has been proposed in recent literature [7, 8]. The acoustic emission (AE) method represents one of NDT and structure health monitoring (SHM) methods for the detection and identification of growing

material defects [9]. With its sensitivity to microstructure and its intimate connection with failure processes, AE inspection can give unique insights into the response of material to applied stress. Mechanisms that produce AE in metals during fatigue loading include the movements and multiplication of dislocations, slip, fracture and debonding of precipitates or microcrack formation and growth [10]. It is very important for study of the early manifestations of fatigue damage and to describe the evolution of fatigue crack in this paper.

Characterization of fatigue damage in structural materials using AE technique has been investigated by several researchers. The bending fatigue behaviour using techniques of signal classification by type of sources (microcracks, dislocations) has been examined in [11]. It was for instance found that the formation of microcracks and their development to the size of the macro-cracks accompanied by an increase in count of AE signals emitted by dislocations and microcracks. In other work [12], it was found that crack initiation indicated by rapid increase of AE count values at positive peak stress and followed by high AE count values around zero stress which indicate crack closure phenomena. AE activity was divided into 3 region which correspond to crack incubation stage, slip plane formation stage and crack initiation and propagation stage. The work [13] deals with the characterization of AE signals from fatigue fracture in a steel specimen under torsional loading. Three stages of fatigue by AE waveform characterization was identified and by microscopic replica observation confirmed.

The above mentioned works are evidence that by monitoring AE during fatigue loading, the sequence of failure processes can be easily detected and catastrophic fracture can be anticipated, in real-time. The main goal of this study is to propose a methodology for evaluation of the early manifestations of fatigue damage under bending loading and to describe the evolution of fatigue crack by AE parameters then.

2. EXPERIMENTAL PROCEDURE

2.1 Material and microstructure

Chemical compositions of Inconel 713LC (in wt. %) was: 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 Velká Bíteš a.s.

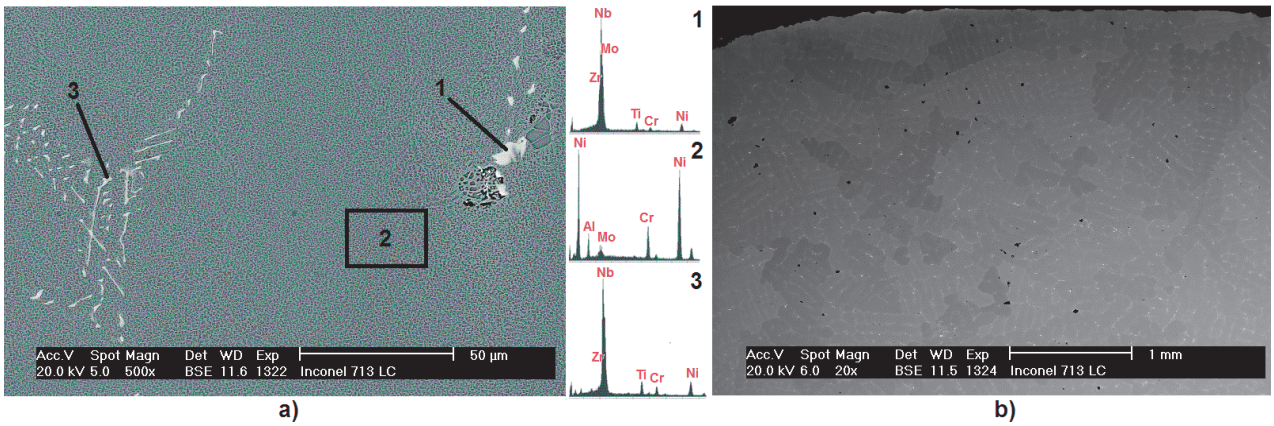


Fig. 1 SEM microstructure of Inconel 713LC: a) 1, 3 - carbides of Nb, Mo, Zr; 2 - solid solution γ with hardening precipitates γ' b) microstructure with casting defects

The microstructure consists of solid solution γ with fine hardening coherent precipitates γ' (Ni_3Al or $Ni_3(AlTi)$) - can be recognized in **Fig. 1a** area "2" . Non-coherent carbides of Nb, Mo, Zr can be seen in interdendritic area and at grain boundaries in a form of 'Chinese characters', **Fig. 1a** "1" and "3". The structure of material is made up of coarse dendritic grains. The grain size determined by means of linear method was 0.68 mm. Despite the fact, that grains are coarse they are 3-6 times finer than in comparison with works of [3, 4, 5] in nominally

identical material, **Fig. 1b**. Microstructure also shows typical casting defects - shrinkage porosity - relatively uniformly distributed black points in **Fig. 1b**. It's one of reasons why fatigue data of cast materials exhibit large scatter [3].

2.2 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. The fatigue cycle was sinusoidal with a frequency about 114 Hz and the stress ratio was set to R = -1. The specimens were generally fatigued until failure.

2.3 AE testing procedure

AE 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 linear location system shown in **Fig. 2** and **Fig. 3**. Results include linear source location, analysis of the number of acoustic waves (AE events), count rate and RMS. Source location is determined by the AE system calculating the time difference between the arrival of the same acoustic wave at the two sensors. AE wave velocity (4300 m/s) was determined before tests by means of Pen-test (Hsu-Nielsen source).

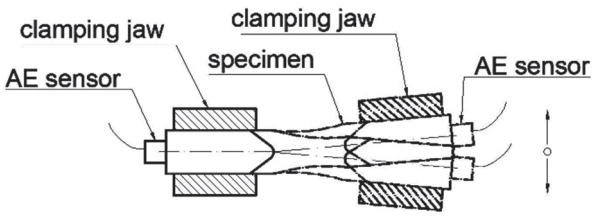


Fig. 2 Schematic illustration of specimen loading

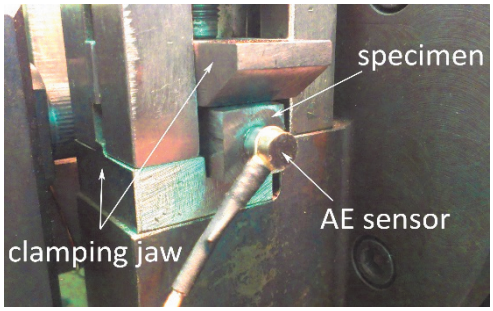


Fig. 3 Location of AE sensor

3. RESULTS

3.1 Results of fatigue test

Measured data were smoothed by Kohout-Vechet's and Stromeyer's regression function, see **Fig. 4**. Above approximately 5x10^6 cycles, both curves are practically identical. However, below this number of cycles Kohout-Vechet's function is more suitable for description of fatigue behaviour of structural metals.

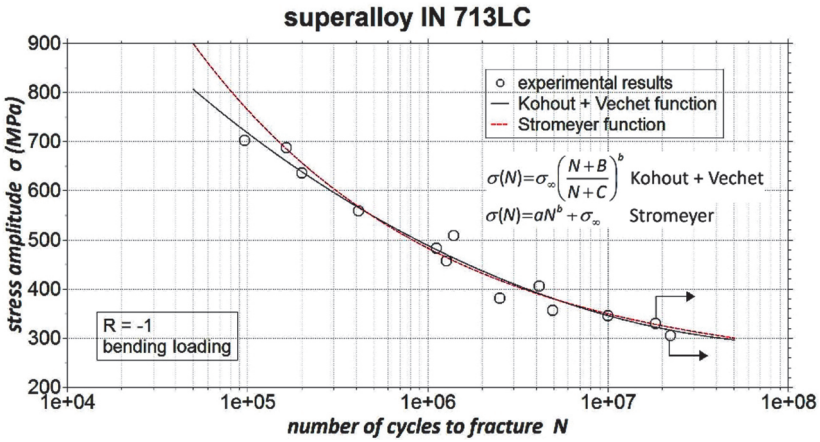


Fig. 4 S-N curves of Inconel 713LC

The fatigue strength at 10^7 cycles was about 340 MPa. Presented curve lies approximately 150 MPa above curve measured in similar conditions by Slamecka et al. [5]. It's probably caused by difference in grain size. **Fig. 5a** shows fracture area of specimen from middle of the measured range (509 MPa). Dendritic structure can be recognized on the bottom of fracture area. In **Fig. 5b** is detailed view on fatigue crack initiation site.

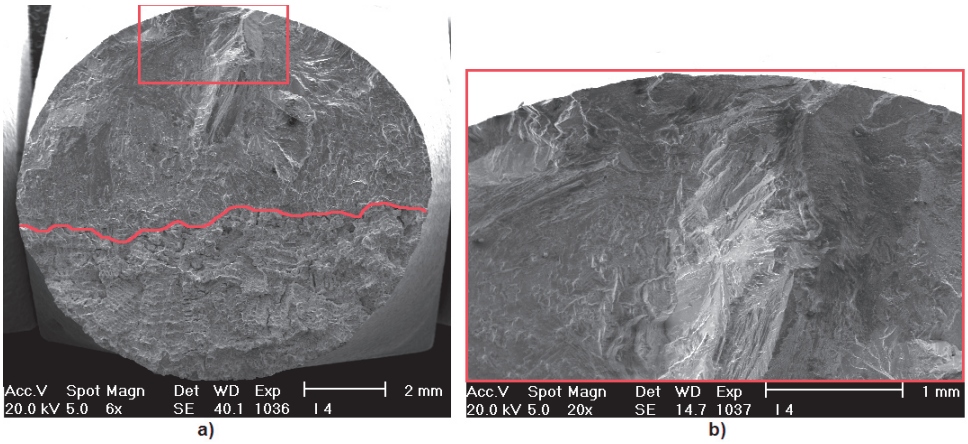
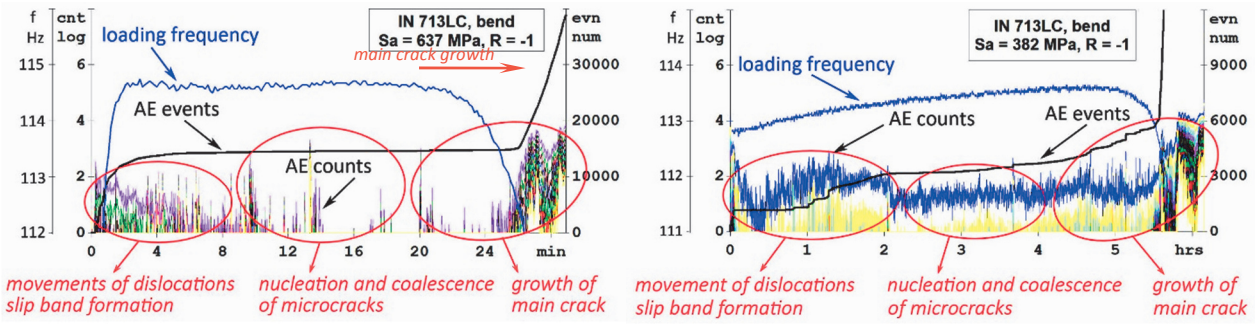


Fig. 5 Fatigue fracture surface of Inconel 713LC (σ_a = 509 MPa, N_f = 1.383x10^6 cycles)
a) overview of the fractured surface, b) detail of crack initiation place

3.2 AE response during fatigue loading

The AE technique has been used to characterize fatigue damage accumulation, and to correlate the signal parameters (such as the AE counts, the peak amplitudes and the energy) with the defect formation mechanisms, and of course, with registrations of loading (resonant) frequency changes for the tested specimen taken with RUMUL fatigue machine. A typical AE response to the high-cycle loading of superalloy Inconel 713LC at selected stress levels is shown in **Fig. 6**.

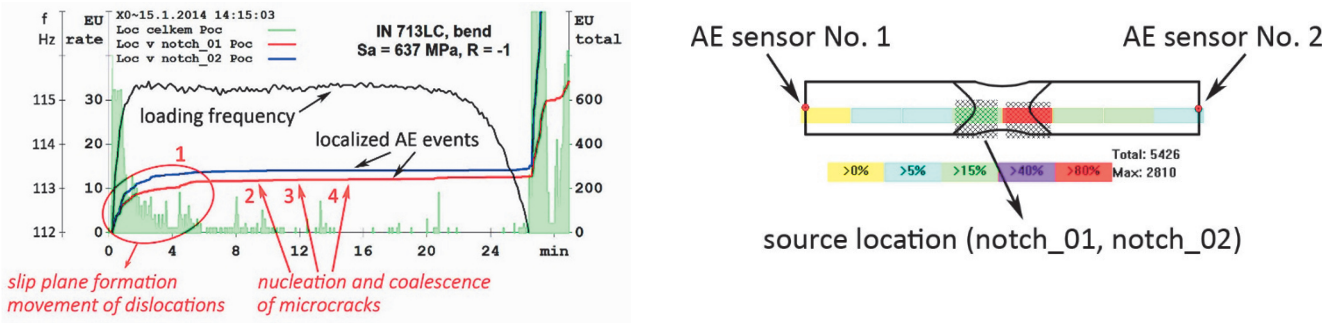


a) b)

Fig. 6 Graphs of AE signals accumulation (count rate - cnt [log], AE events - evn [num]) and loading frequency (*f* [Hz]) during the fatigue test to failure of Inconel 713LC at different stress levels:
a) σ_a = 637 MPa, N_f = 1.98x10^5 cycles; b) σ_a = 382 MPa, N_f = 2.5x10^6 cycles

It was found that at all stress levels, AE counts and events were high in the first period due to mechanical properties changes (movement and interaction of dislocations and persistent slip band formation). The crack nucleation stage was characterized by low activity of AE signal with occasional peaks, in comparison with other stages, see **Fig. 7a**. The course of loading (resonant) frequency was useful to identify the beginning of the main crack growth. It is interesting that the AE signal response to main crack propagation is significantly delayed. This confirms the existence of different crack growth stages and a very high AE activity at near-fracture period indicates the unstable fatigue propagation. The location distribution histogram of all AE events

accumulated during the fatigue life of specimen (**Fig. 7b**) shows that most of the emission was generated at the notch.



a) b)

Fig. 7 AE source location and damage mechanisms identification. a) Localized AE events and frequency loading vs. time; b) Source location on the specimen surface

With waveform-based analysis, the signals can be analysed in detail and used to relate any changes in waveform features to possible development of fatigue damage mechanisms. There were found significant changes in the amplitude and frequency spectrum of the waveforms during the first (early emission - movement of dislocations, slip band formation) and second stage of the fatigue damage (fatigue crack initiation). Typical AE signal taken from the first two stages are shown in **Fig. 8**. Numerical designations of stages in **Fig. 7** correspond with those in graphs in **Fig. 8**.

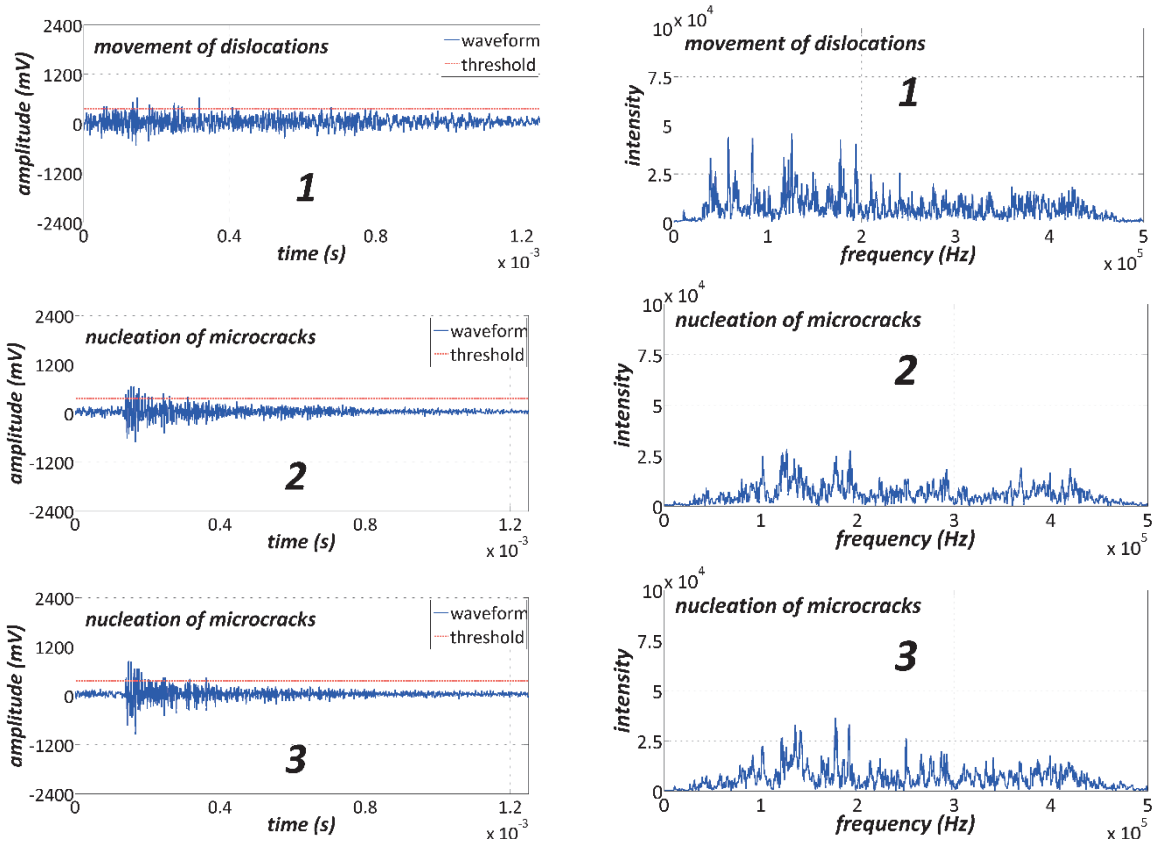


Fig. 8 Typical AE waveform (on the left) and its frequency spectrum (on the right) in pre-initiation and initiation stage. Numerical designations in graphs correspond with those in **Fig. 7**.

CONCLUSION

High-cycle bending fatigue assessment of Inconel 713LC and the analysis of AE response of this material was presented. The experimental data obtained from the fatigue tests were smoothed by Kohout-Vechet's and Stromeyer's regression function. The fatigue strength at 10^7 cycles was about 340 MPa. Presented curve lies approximately 150 MPa above curve measured in similar conditions by [5]. Fatigue life of the material is probably influenced by finer grain structure by analogy with Hall-Petch law.

The AE measurement during fatigue tests was especially focused on the first two stages, i. e., the mechanical properties changes and fatigue crack initiation stage. Typical waveforms were correlated with fracture mechanism from different stages of fatigue damage. It was found that count rate parameter is most sensitive to the initiation and coalescence of the fatigue crack. Crack initiation indicated by low activity of AE count values and at 130 and 175 (190) kHz of power spectral density.

Consequently, AE offers the ability to detect and anticipate fatigue crack propagation accurately and provide early warning to fracture and is very useful tool of the fatigue assessment.

ACKNOWLEDGEMENTS

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