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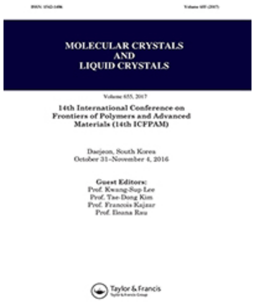


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# Estimating mechanical state of AA2024 specimen under tension with the use of Lamb wave based ultrasonic technique

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**ABSTRACT**
Experimental results on application of ultrasonic technique utilizing Lamb waves for evaluation mechanical state of AA2024T3 specimens under tensile testing are presented. PZTs used as actuators and sensors were glued onto the specimen surface with epoxy adhesive. The set of static tensile tests with two frequencies of acoustic testing (50 kHz and 335 kHz) were performed. The recorded signals were processed to calculate the informative parameters (maximum envelope and 2nd central moment) in order to evaluate the changes of the stress-strain state of the specimen and its microstructure evolution. The relations between acoustic signal features and damages occurring during the loading allow determining the defectiveness of the structure and predicting its residual lifetime.

**KEYWORDS**
Acoustic spectroscopy; lamb waves; structural health monitoring; ultrasonic testing



## Introduction

Non-destructive testing is of crucial importance at any stage of the lifecycle of the industrial products. There are a lot of NDT methods based on various physical principles being applied for inspection of newly manufactured parts and units to detect different flaws and damages. The inspection during operation is a more complex problem since the vehicle should be stopped; sometimes it should be disassembled, which lead to financial losses. Wherein the NDT statistics with defined lifetime intervals shows that the damages occur in a rather small number of tested objects while time and funds for inspection of the rest were wasted. However the inspection intervals cannot be expanded because the structures where the damages have been already nucleated can experience the catastrophic failure which is inappropriate for different application: aerospace, petrochemical, etc.

In recent years the NDT scientific and engineering community is increasingly interested in research and development of the Structural Health Monitoring (SHM) systems [1–3]. The SHM concept is based on the design and embedding of sensing network into structure, recording of the initial data during the operation and its further processing to obtain the strain data or to detect the damage for timely maintenance. The SHM can be used to expand the

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inspection intervals if the system does not register the significant changes exceeding the defined threshold. There are different SHM principles proposed by different research groups, e.g. the strain sensing using optical fiber [4]. The obtained value is compared with the baseline of non-damaged structure thus revealing the damage. These systems should register the data during whole operation time (e.g. during aircraft take-off, flight, landing and taxiing). Another SHM approach [5] utilizes the network of ultrasonic transducers embedded in the structure being applied for direct detection of discrete damage (BVIDs and delamination for CFRP, cracks in metal alloys, etc.). Online monitoring for such systems is unnecessary moreover it can be distorted due to noise and vibration, so the initial data is obtained after defined lifetime intervals. These systems [6–8] are used for operational load monitoring and can expand the inspection periods.

All SHM approaches require the development of complex algorithms and software for data processing and continuation of operation decision-making. The basis for the software is a deformation mechanics of different materials. To test the designed system and software the joint consideration of experimental data and computer simulation is required. There are a lot of papers dealing with the research of ultrasonic systems utilizing Lamb wave principle and algorithms for damage detection. However in most of them the PZTs without substrate are used. Such PZTs will be inappropriate for cyclic loading during operation due to brittleness of piezoceramic. The aim of the present study is to assess the applicability of PZTs with steel substrate for fatigue failure evaluation. The experimental results of ultrasonic evaluation using Lamb waves of AA2024T3 specimens tested under static and cyclic tension are described in the paper.

## Materials and technique

The investigation of proposed ultrasonic technique was performed during static and cyclic uniaxial tensile testing of the AA2024T3 specimens. The drawing of the dogbone-shaped specimen used for testing is presented in Fig. 1. The static tensile testing was carried out using electromechanical machine Instron 5582 with the load rate of 0.3 mm/min. Cyclic loading was performed at employment servohydraulic testing machine BiSS UTM 150kN with the load ratio R = 0.1, 10 Hz loading frequency and $P_{max}$ defined as $0.8\sigma_b$. The piezoelectric transducers used as actuators and receivers are piezoceramic discs with diameter of 9 mm and thickness of 0.19 mm on steel substrate AW1E12G-190EFL1Z by Audiowell Corp. The PZTs were glued on the specimen's surface using 3M Scotch-Weld DP490 epoxy adhesive (the tests were carried out after full polymerization of the adhesive during 7 days). The 1st PZT was used as an actuator. The 2nd (to characterize the changes outside the highly stressed gage length

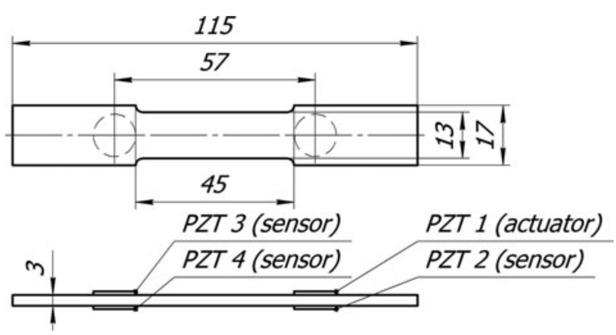


**Figure 1.** The drawing of the specimen, the position of the PZTs is schematically described.

of the specimen), the 3rd and the 4th (to evaluate the changes within the gage length) were used as receivers. The ultrasonic signals were generated using arbitrary waveform generator AWG-4105 with the amplitude of 10 V and the frequency in the range from 10 to 500 kHz. The 5-cycle sine modulated by Hanning-window was used as a testing signal (Fig. 2).

The signals were recorded using USB oscilloscope Handyscope HS4 with the sampling rate of 5 MHz and 12 bit resolution. To increase the S/N ratio the averaging of 100 recorded signals was performed. The signal recorded straightly from the generator by the 1st channel of HS4 was used as the timing reference. The registered signals were processed using band-pass 10–800 kHz filtering. The signal acquisition from sensor PZTs was triggered by the reference signal. The recorded acoustic signals were processed to calculate two parameters in order to characterize fatigue state on different specimen lifetime: maximum envelope and the 2nd central moment of two envelopes difference.

The calculation of the maximum envelope of received ultrasonic signal was carried out using Hilbert transform procedure in the frequency domain [5]. The signal amplitude is calculated as the maximum of its envelope – MaxEnv or Amplitude. To evaluate the changes of the ultrasonic signal during cyclic loading the calculation of the 2nd central moment of two envelopes difference for initial and current states of the specimen was used. The first recorded signal corresponds to the nondeformed state of the specimen. The subsequent signals were registered during cyclic loading after the specified number of cycles. Then the envelopes difference is calculated according to [6]. The parameter is designated as *m*2.

There are two experiments performed for the uniaxial static tension. In the first one the step mode loading was used and the signals were recorded when the specimen was fixed in grips in the unloaded state. Thus the influence of the adhesive layer deformation and residual strain of the specimen were assessed. In the second one the static uniaxial tensile loading was applied continuously with the terminations in specified points for data acquisition (the specimen was fixed in grips being subjected to tensile load). So the dependence of the recoded signal amplitude on the stress-strain state was investigated. The main goal of the static tests is to investigate the response of the actuator-receiver pairs during loading and to ensure the possibility of PZTs and epoxy adhesive application for further fatigue evaluation of the AA2024T3 specimens. The cyclic loading experiment was carried out in the following manner: after the

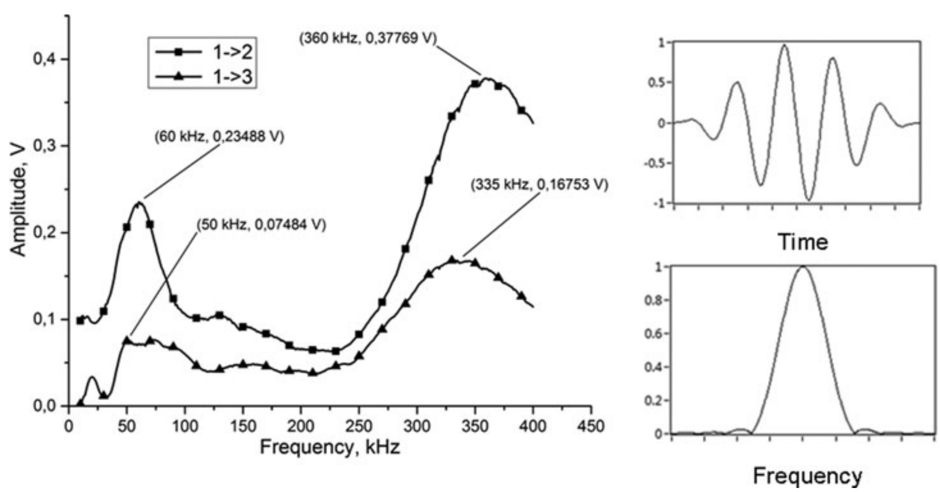


**Figure 2.** The dependence of the received signal amplitude vs the frequency. There are two actuator-sensor responses: from 1st PZT to 2nd (through thickness of the specimen) and from 1st to 3rd (through the gage length). The examples of the signal in time and frequency domains are shown.

cyclic loading with defined number of cycles the loading was stopped and the $P_{min}$ was set to record the ultrasonic testing data. The registered acoustic signals were processes to calculate the two parameters in order to characterize mechanical state under fatigue at various specimen lifetime.

## Results and discussion

**Static tension**. The choice of the frequency for ultrasonic testing was based on the results of preliminary study of the response within the range from 10 to 400 kHz of the actuator-sensor couples being glued on the specimen's surface. The signal registration was performed with the frequency step of 1 kHz; the received signal amplitude was calculated and thus two graphs were obtained (Fig. 2). They represent the signal registered by the 2nd and the 3rd PZTs. First of all, this dependence was plotted to characterize the amplitude-frequency response of the PZTs used in the study. It is easily seen that the curves are similar in concern of the decrease of the amplitude due to attenuation of the signal during its propagation through the gage length.

This investigation is aimed at finding out the possibility of using ultrasonic technique to characterize the changes in a specimen state to occur due to the deformation as well as microstructural changes of the material in the highly stressed gage length. Thus the frequency was chosen for signal propagation through the second path (1→3): for the static testing the values of frequency being corresponding to the peaks of 50 and 335 kHz were used.

Figure 3 represents the stress-strain curve of the AA2024T3 specimen loaded in step manner until fracture: there are 34 points of predefined load values where the loading was terminated and the ultrasound testing was performed. It should be noted that the elongation was measured with the transducer of the testing machine and certain increasing takes place due to the indentation of grips into the specimen, while the gage length at the elongation calculation does not account for this increment. The yield point is easily recognized at 300 MPa (4.5–5 % of elongation). It is easily seen that after reaching the yield point the inelastic deformation occurs and the specimen is deformed irreversibly.

Figure 4 represents the amplitude of the recorded at 50 kHz signal (unloaded condition, the specimen is fixed in grips). The black curve (squares) is a graph of amplitude of the signal propagated through the thickness from 1st PZT to 2nd one. The red curve (triangles) was recorded when the signals were sent from 1st to the 3rd PZT through the specimen gage

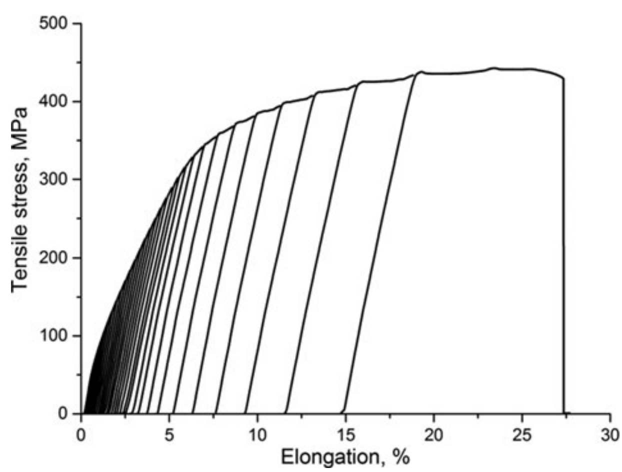


**Figure 3.** The stress-strain curve for the tension test of the AA2024T3 specimen.

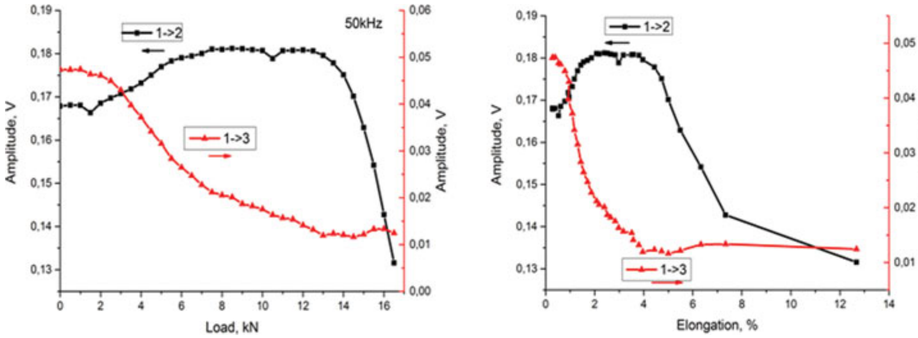


**Figure 4.** The graphs to illustrate the dependence of signal max amplitude vs the load (a) and elongation (b) at the sounding frequency of 50 kHz.

length. The 1→2 signal amplitude increases slightly at the first stage of loading (up to 2 % of elongation) then it keeps constant up to necking. Then the substantial decrease of recorded signal amplitude is registered due to inelastic deformation. The red curve possesses different behavior: the amplitude of the registered signal decreases by four times during elastic stage of the loading. This can be explained through the fact that that the low frequency (50 kHz) Lamb waves are sensitive to the indentation of grips into the specimen surface during first stage of loading. Then after reaching the yield point the amplitude stays constant until fracture.

Figure 5 shows the graphs of the received signal amplitude at the frequency of 335 kHz. The PZT on this frequency have the highest sensitivity (Fig. 2), thus the higher values of amplitude 0.42 V against of 0.18 V for the 50 kHz are obtained. The both curves behave similarly: before the yield point the amplitude does not changes at all. Then during subsequent loading (within inelastic deformation) the registered signal amplitude prior to the fracture point is decreased by ~20 %. This can be explained through the geometry changes of the specimen due to plastic deformation (necking) as well as microstructure changes in the material.

Figure 6 shows the stress-strain curve recorded during the continuous tensile test (without the specimen unloading) and the graph of the registered signal amplitude. It is easily seen that both curves are similar. It can be concluded that the ultrasonic testing used is sensitive to the stress-strain state of material. During the elasticity the amplitude also increases linearly; at reaching the yield point the shape changes to nonlinear one since inelastic deformation starts. Then the amplitude increases linearly up to fracture.

Cyclic tension. The frequency of 50 kHz for ultrasonic tests was chosen just like in above described previous experiments of Lamb wave based technique for evaluation of AA2024T3

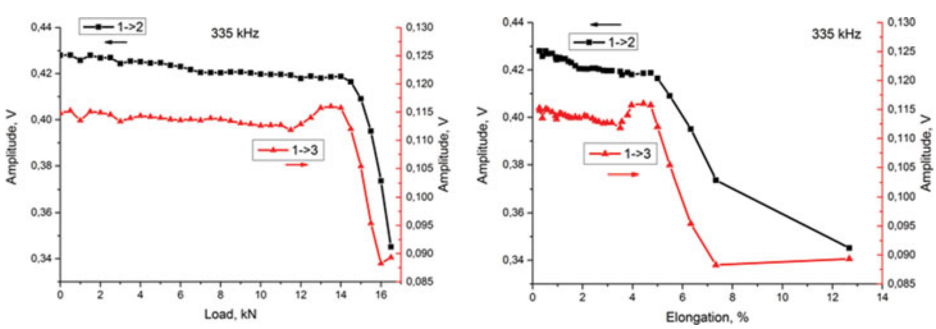


**Figure 5.** The graph to illustrate the dependence of signal amplitude vs the load (a) and elongation (b) at the sounding frequency of 335 kHz.

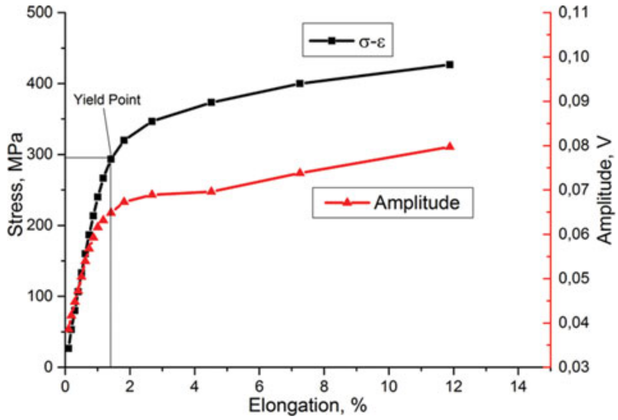


**Figure 6.** The combined graph of the stress-strain curve and the dependence of the 50 kHz signal amplitude vs the elongation of the specimen.

specimens under static tension. The fatigue tests were carried out and the set of acoustic signals were recorded. Figure 7 shows the shape of the registered acoustic signal and their diagram of wavelet coefficients for two PZT sensors which were mounted on the different sides of the specimen. The signals represent the base signal in unloaded specimen.

Time of arrival (the peak with the highest amplitude for PZT4 is 265 data points ∼53 μs) corresponds well to the lowest valley for PZT3 and shows that the first wave package is a zero antisymmetric Lamb wave mode ($A_0$). At the same time it is not possible to recognize the arrival of symmetric mode ($S_0$) due to its very low amplitude at the frequency of 50 kHz. Longer distance, higher frequency or lower specimen thickness could enlarge the time difference in future experiments.

Time of arrival of the sensed signal changes during cyclic loading insufficiently thus it is impossible to make any precise analysis. Stable time position could be explained by small distance between actuator and receiver and long wavelength. As a result of two mentioned facts the interaction of acoustic waves with fatigue induced defects is not enough to change the time of flight.

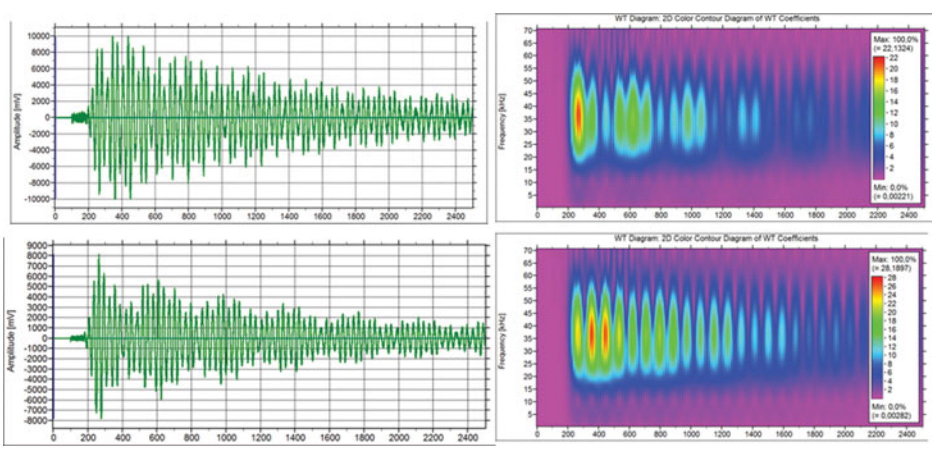


**Figure 7.** The shape of the received signal for PZT3 (on top) and PZT4 (at the bottom) at the left side and wavelet analysis of the received signal at the right side

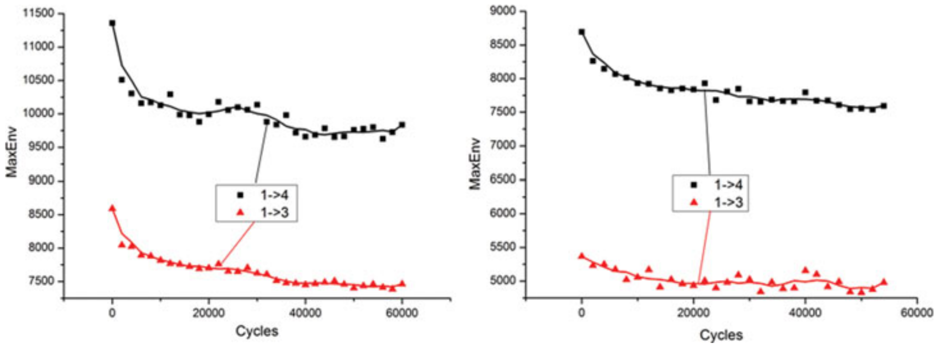


Figure 8. Maximum envelope vs number of cycles (specimen A – on the left, specimen B – on the right)

The signals were processed to obtain two informative parameters: Max Envelope and the 2nd central moment. The results for two specimens with the cyclic lifetime of 62 000 (specimen A) and 55 000 (specimen B) are presented in the paper.

The results of Max Envelope calculation for the two specimens are presented in Fig. 8. The graphs were smoothed using averaging. Maximum envelope drops after 2 000 cycles and then slightly decreases all the time up to the fatigue failure. It means that on the first stage the rate of damage accumulation is very high and defects significantly influence on the attenuation of acoustic waves. At the second stage the monotonic and smooth reducing of the amplitude take place till the end. The decreases of the maximum envelope from the initial values for different specimens and PZTs are:

- from 8590 to 7387 in specimen A, PZT 3 Path 1->3 (by 16%);
- from 11361 to 9625 in specimen A, PZT 4 Path 1->4 (by 18%);
- from 5366 to 4828 in specimen B, PZT 3 Path 1->3 (by 11%);
- from 8694 to 7539 in specimen B, PZT 4 Path 1->4 (by 15%).

Additionally it should be mentioned that amplitude for the transducers located on the opposite side from the actuator is higher than for the transducers located at the same face with the actuator.

The results for the 2nd central moment of envelope difference calculated for the two specimens are presented on Fig. 9. The graphs were smoothed through the averaging technique [9].

During cyclic loading procedure the specimen accumulate defects and it provides crack growth, thus initial signal will be distorted. The level of such distortion could be evaluated

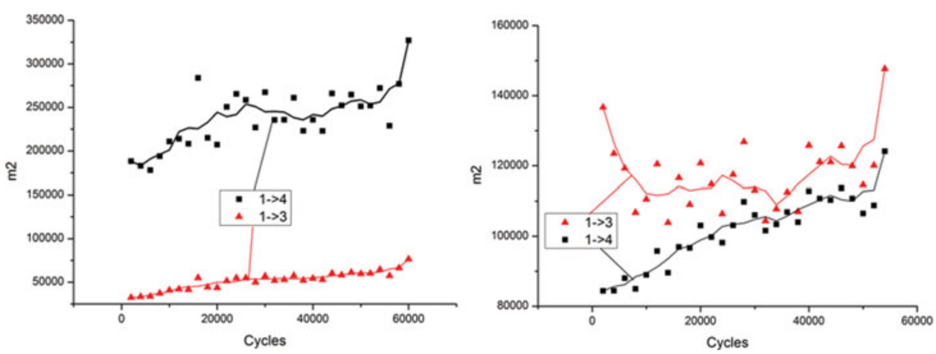


Figure 9. 2nd central moment of envelope difference vs number of cycles (specimen A – on the left, specimen B – on the right)

by 2nd central moment parameter. The latter characterizes the difference between initial and current state signals at each step of cyclic loading test. During the experiment a crack growth as well as micro cracking takes place, therefore the signal distortions will increase. The phenomenon is directly visible on the curves of 2nd moment for the PZT3 and PZT4 (specimen A) and for the PZT4 (specimen B). These changes have the following absolute values:

- 32290 – 76534 specimen A, PZT 3 Path 1->3 (130%);
- 188312 – 327038 specimen A, PZT 4 Path 1->4 (70 %);
- 136671 – 147688 specimen B, PZT 3 Path 1->3 (10 %);
- 84373 – 124108 specimen B, PZT 4 Path 1->4 (50 %).

The curve of 2nd moment for the specimen B and PZT 3 (Path 1->3) does not demonstrate unequivocal behavior, though it has ascending trend.

## Conclusions

The results obtained during the static testing confirm the possibility of application of used ultrasonic PZTs for fatigue damage sensing. The graph in Fig. 4 and Fig. 5 show that the adhesive layer and the PZTs are not affected by the strains due to loading within the yield stress. The loads for fatigue testing lie below the yield point and we can apply investigated PZTs as actuators and sensors for further fatigue testing. Analysis of results obtained during fatigue experiments shows that proposed technic for integral structural damage and health evaluation is sensitive to characterize damage nucleation under cyclic testing. The dependence of signal characteristic parameters on the number of cycles was determined and the behavior of these parameters is not linear It allows one to characterize the state and processes, which arise within the material during cyclic loading.

According to the alignment of sensor-generator it could be concluded that the pass generator-PZT4 (on the opposite sides of the specimen) is more sensitive to defects accumulation processes and crack growth as the pass generator-PZT3 (on the same face of the specimen).

## Acknowledgements

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## Declaration

The paper A. V. Byakov, A. V. Eremin, R. T. Shah, M. V. Burkov, P. S. Lyubutin, S. V. Panin, P. O. Maruschak, A. Menou, and L. Bencheikh. Estimating mechanical state of AA2024 specimen under tension with the use of Lamb wave based ultrasonic technique is original and not submitted for publication in another journal Prof. Pavlo Maruschak.

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