Technical Physics, 2025, Vol. 70, No. 5

10

Acoustic Emission Damage Accumulation Monitoring during Mechanical and Thermal Strain of Paratellurite Single-crystal

© A.S. Machikhin,[1,2] A.Yu. Marchenkov,[1] D.V. Chernov,[3] T.D. Balandin,[1,3] M.O. Sharikova,[1,2] A.A. Bykov,[1,2] D.D. Khokhlov,[1,2] Ya.A. Eliovich,[4] Yu.V. Pisarevsky,[4] A.A. Pankina[1]

[1] National Research University „Moscow Power Engineering Institute“,
111250 Moscow, Russia
[2] Scientific and Technological Center of Unique Instrumentation Russian Academy of Sciences,
117342 Moscow, Russia
[3] Blagonravov Institute of Machine Science, Russian Academy of Sciences,
101990 Moscow, Russia
[4] Kurchatov Complex Crystallography and Photonics, NRC „Kurchatov Institute“,
119333 Moscow, Russia

e-mail: art-marchenkov@yandex.ru

Received October 15, 2024
Revised February 6, 2025
Accepted February 6, 2025.

The paper considers the problem of detecting defects in paratellurite single crystals using the acoustic emission method. For the first time, research was conducted on single crystals of natural geometry installed in an acousto-optic cell used in devices such as acousto-optic modulators, deflectors, and spectral filters. It was found that high-frequency acoustic signals in the operating frequency range of 27–60 MHz do not affect the registration of acoustic emission signals. Complex criteria were proposed and experimentally confirmed that allow one to detect moments of formation of crack-like defects in paratellurite single crystals under the action of mechanical stresses and temperature gradients based on the parameters of acoustic emission signals. The proposed approach allows one to determine the actual state of a paratellurite single crystal under the action of both mechanical and temperature stresses.

Keywords: strain, crystal, paratellurite, acoustic emission, statistical analysis, amplitude-frequency response.

DOI: 10.61011/TP.2025.05.61134.18-25

Introduction

Crystalline materials play a key role in modern opto-electronics and are widely used in manufacture of electronic components, communication and navigation devices, optoelectronics and acousto-optics, and measuring equipment [1]. The ever-increasing requirements for operational reliability, limits of permissible environmental exposure, weight and dimensions imposed on electronic photonics and optoelectronics devices determine the increasing demand for high quality (purity, structural uniformity, etc.) of single crystals, which are often their key components. All natural and synthesized single crystals and, to an even greater extent, polycrystalline crystallites differ from ideal ones in that they contain various structural disorders. Structural defects of crystalline materials include violations of the ideal translational symmetry of the crystal lattice, which can significantly affect their properties: electrical conductivity, photoconductivity, thermal conductivity, diffusion rate, hardness, strength and plasticity, density, etc. [2,3].

The industrial manufacture of crystal-based functional elements is a complex multi-stage process that requires the use of precision methods for the crystal structure abnormalities detection, since the degree of structural perfection of crystals largely determines the performance characteristics of devices fabricated on their basis. This is especially important in the manufacture of devices designed to operate under extreme conditions or under environmental exposure, for example, under mechanical loads, high temperatures, and electric fields. Studies of crystals under environmental exposure can serve as a model for studying the behavior of ready-to-use devices and their components, as well as help determine their ultimate functional characteristics.

The currently developed methods of crystal diagnostics, in particular, electron microscopy, atomic force microscopy, X-ray diffraction, and some others, allow obtaining information about defects at an atomic level, however, as a rule, these methods require sample preparation or do not allow studying the dynamics of the defective structure *in-situ*, and provide information about the internal structure of the studied material only at one specific moment of time without analyzing the defects progress from the early stage of their formation to moment of crystal destruction.

To overcome these limitations, the acoustic emission (AE) method based on the analysis of elastic waves characteristics during formation and growth of defects seems to be promising [4]. Earlier, the effectiveness of this method was demonstrated by studying samples of paratellurite crystal TeO_2 [5] — one of the most effective acousto-optical (AO) materials in visible and near infrared (IR) spectra, with an unusual combination of material constants and physical properties, and widely used in modulators, deflectors, spectral filters and other devices [6].

High sensitivity of AE method allows conducting an early diagnostics of damages in the material of controlled products. Based on the existing estimates of the experimental findings [4], the process of the crack growth to a length of about 1 μm and more can be detected using AE method. As known, the origination of defects (for example, crack propagation) in the material of the controlled product is accompanied by relaxation of elastic mechanical energy, which in AE method is detected using piezoelectric sensors in the ultrasonic range — usually in the range from 30 to 1000kHz.

AE pulse standing for the defect growth has an oscillating shape with a short rise time and a significant fall time, and its processing is mainly carried out according to the primary AE parameters — amplitude (u_m), duration (t_i), rise time (t_φ), number of pulse overshoots (N_i). Based on the results of AE data processing, it is possible to distinguish between acoustic emission sources of different origins. E.g., signals from friction and defect growth processes may be separated based on the values u_m and t_i. Friction processes generally initiate the low-frequency AE pulses of long duration t_i, and material brittle fracture processes — trigger the high-frequency AE pulses of large amplitude.

To obtain dependable AE monitoring results, it is necessary to use the advanced signal processing methods based on estimation of changes in the dynamics of both, primary [7–11] and complex parameters [12–14]. The use of complex parameters, for example, statistical characteristics of energy distribution functions (E_i) or the average emission frequency (N_i/t_i) of recorded signals, is due to the need to increase the stability of AE diagnostics results. As shown in [12–14], at the moment of formation and development of an irreversible damage, a change in the distribution parameters of energy and duration of AE pulses is observed, which makes it possible to obtain the analytical dependences $E_i(t_i)$ and $u_m(E_i)$, which correlate with the degree of damage to the single-crystals.

In this work, for the first time, acousto-optical cells (AOC) made of paratellurite used as tunable spectral filters were studied using AE. The shape of paratellurite crystal used in AOC and the orientation of its axes differ from the parallelepiped samples [5,15], which allows considering the experimental conditions as the most close ones (from those conducted so far) to the actual functioning of an AO device.

AOC made of TeO_2 crystal with transect angle of $\gamma = 7°$ and output facet angle of $\beta = 2°$ were used as test samples. The single crystal is placed in an aluminum alloy body D16. Figure 1 shows the sketch of such sample. This design underlies tunable AO filters of the most common visible (450–900 nm) and near IR (900–1700 nm) bands. This configuration of AO filters is unified and provides high-quality spectral images in a wide range of wavelengths 450–1700 nm with a confocal optical scheme of wide-aperture anisotropic AO diffraction in TeO_2 crystal [16]. To provide specific spectral operating band of an AO filter it is necessary to apply a piezoelectric sensor (PES) of the required thickness, ensure electrical matching in the frequency bands 60–120 MHz (450–900 nm) and 27–60 MHz (900–1700 nm) and apply an antireflection coating on the input and output optical facets.

This paper provides an insight on a possibility of acoustic emission monitoring of the damages that may accumulate in a single crystal of paratellurite used in AOC under the impact of mechanical and thermal stresses. The studies were carried out in three stages.

1. Evaluation of the effect of a high-frequency acoustic signal on the parameters of the detected AE pulses in the diagnostics of a single crystal of paratellurite

At the first stage, the influence of a high-frequency acoustic signal applied to the single crystal of TeO_2 during its operation on the parameters of detected AE pulses was evaluated. The diagram of the experiment is shown in Fig. 2.

High-frequency acoustic signal (HF) in the frequency band f_{ae} from 27 to 60 MHz and power of 0.5 W was applied to the piezoelectric sensor (PES) mounted on a single crystal of paratellurite. Such frequencies correspond to AO filter reconfiguring in the wavelength range of 900–1700 nm due to occurrence in the crystal of a dynamic volumetric diffraction grating which, due to selective Bragg diffraction of incident light, is used to isolate a given spectral component from the light beam λ.

AE pulses were detected using „VS150-RIC" AE transducer with a built-in preamplifier with a gain coefficient of 34 dB connected to „Vallen AMSY-6"system of acoustic signals detection and processing. AOC together with acoustic emission transducer (AET) was installed into the waveguide (WG) — a steel plate 8 mm thick — through a layer of contact grease („Lithol-24") to provide acoustic contact, at a distance of 30 mm relative to each other. The paratellurite single crystals were installed in AOC by means of a sliding fit, which provided the required acoustic contact and easy extraction of the single crystal from AOC.

In the presence of a good acoustic contact, any acoustic effect on AOC body or single crystals of paratellurite leads to transmission of these vibrations through the waveguide to the acoustic emission transducer at a certain rate v_{ae}. To check the acoustic contact between the acoustic emission sensor and the control object on the side facet of AOC, AE pulses were generated using a Nsu-Nielsen simulator (mechanical pencil lead breakage). Maximal amplitude of detected AE pulses from Nsu-Nielsen simulator was $u_m = 99.2–99.5$ dB, which indicates low level of acoustic signals attenuation in the used waveguide.

For the study, the bandwidth and threshold of AE pulse discrimination were selected $\Delta f = 25–850$ kHz

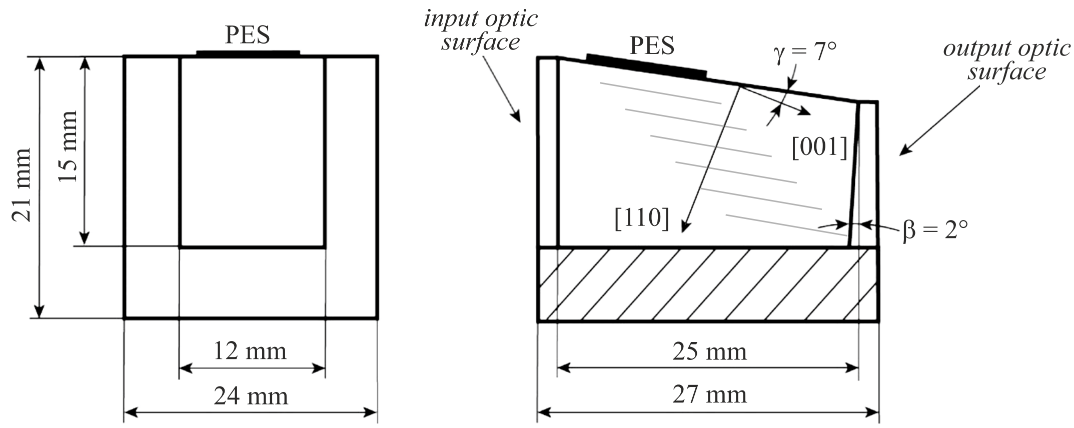

Figure 1. Sketch of AOC samples made of paratellurite in the frame of: PES — piezoelectric sensor, γ — transect angle, β — output facet angle; [001] and [110] — crystallographic orientations.

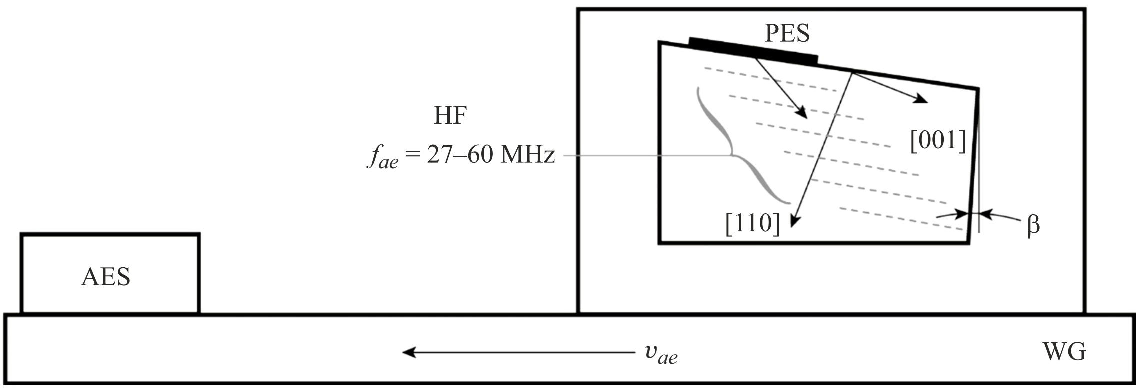

Figure 2. Diagram of acoustic signal excitation in a single crystal of paratellurite installed in AOC: AET — AE transducer; HF — high-frequency acoustic channel; WG — waveguide; f_{ae} — frequency of acoustic signal, v_{ae} — speed vector of acoustic signal.

and $u_{th} = 28\,\mathrm{dB} = 25.1\,\mathrm{mV}$, respectively. The discrimination threshold — is the boundary level of the input voltage of the measuring equipment, above which the signal is evaluated as an AE pulse, and below — as noise. AE pulse discrimination threshold was calculated according to the condition $u_{th} \geq u_n + 6\,\mathrm{dB}$ (u_{th} — AE pulse discrimination threshold, u_n — maximum amplitude of noise signals), regulated by the regulatory document PB 03-593-03. Maximum amplitude of the noise signals was determined based on the results of preliminary tests and was $u_n = 21.6\,\mathrm{dB}$, and the value of the discrimination threshold according to the above condition was selected at $u_{th} = 28\,\mathrm{dB}$. During the experiment, with the use of acoustic emission transducer, temporary noise realizations were recorded for two cases: in the absence of external high-frequency acoustic signal and during generation of an acoustic wave in $f_{ae} = 27{-}60\,\mathrm{MHz}$ band in the single crystal of paratellurite. Temporal realizations of noise as amplitudes of the acoustic signal U recorded by AET versus time t for these two cases are shown in Fig.3. As seen from Fig. 3, the noise realizations of $t = 4\,\mathrm{ms}$ have no visible difference.

For a more detailed assessment of the correlation of noise realizations, a comparison of noise histograms for the presented signals was performed, shown in Fig. 4. To numerically evaluate the similarity of noise signals histograms, the correlation coefficient was calculated, the value of which was $R = 0.9996$, which indicates a complete correspondence of histograms of the considered realizations. The presented dependencies confirm that the detected signals represent the same noise process with similar values of mathematical expectation $x_{\mathrm{OFF}} = 0.50\,\mathrm{mV}$ and $x_{\mathrm{ON}} = 0.48\,\mathrm{mV}$ and mean-square error $s_{\mathrm{OFF}} = s_{\mathrm{ON}} = 7.5\,\mathrm{mV}$ for the cases of absence („OFF") and generation („ON") of an acoustic wave in a single crystal of paratellurite. It should be noted that maximum amplitude of the noise signals did not exceed the value of $u_n = 0.037\,\mathrm{mV} = 31.4\,\mathrm{dB}$.

Thus, the results obtained allowed to unambiguously establish that high-frequency acoustic vibrations in the frequency range $f_{ae} = 27{-}60\,\mathrm{MHz}$ applied to a single crystal of paratellurite during AOC operation in AO devices do not affect the received AE signals in the diagnostic process. This allows the AE method to be used as a method for monitoring the integrity of a single crystal of paratellurite directly in AOC during its operation as part of AO devices.

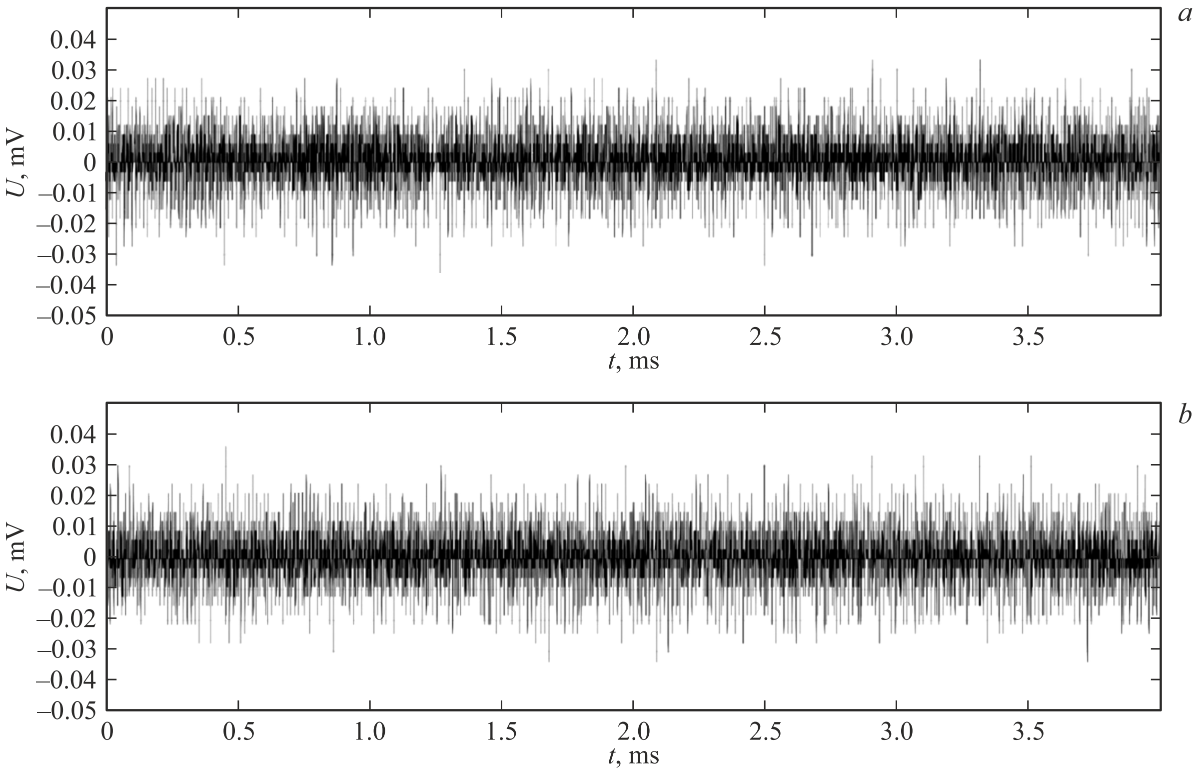

Figure 3. Noise realizations detected by AET for the following cases: *a* — absence of high-frequency acoustic signal; *b* — generation of acoustic wave in a single crystal in $f_{ae} = 27-60$ MHz band.

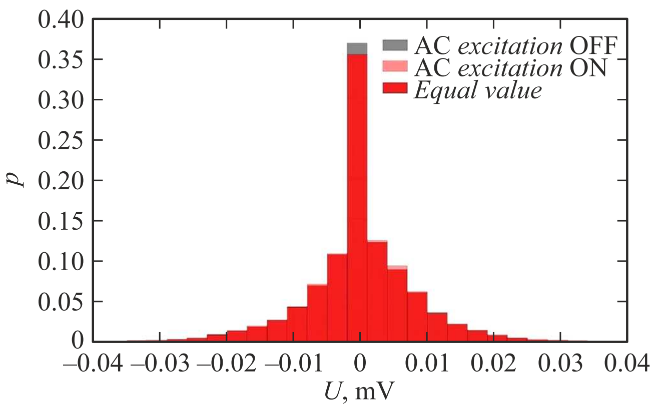

Figure 4. Comparison of noise histograms for cases of absence and presence of the high-frequency acoustic wave in the range $f_{ae} = 27-60$ MHz in a single crystal.

2. Diagnostics of a single crystal of paratellurite in an acousto-optic cell (AOC) by AE method under mechanical compression

The second stage of the experiment consisted in static compression of AOC with a single crystal of paratellurite installed and the use of AE diagnostics system. Paratellurite crystal compression experiments were carried out on an Instron 5982 testing machine. General view of the testing setup is shown in Figure 5. AOC *3* and two AE transducers *1*, pressed by magnetic holders, were mounted on the surface of a steel waveguide in the form of a massive metal base *4* through a layer of contact grease. AOC was compressed by the upper movable die with a floating joint

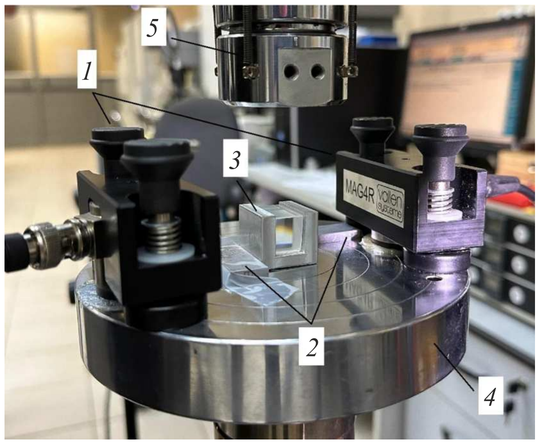

Figure 5. General view of the structure in AOC compression testing: *1* — quasi-resonance AET „VS150-RIC" with magnetic press-holders, *2* — stops to prevent displacements during loading, *3* — AOC from TeO_2 crystal, *4* — acoustic waveguide, *5* — floating joint of the movable die.

base *5*. To eliminate the noise signals occurring during friction of the upper die of the testing machine against the crystal surface, the digital filters bandwidth was selected as $\Delta f = 95{-}850$ kHz.

AOC was deformed with the movement rate of the upper traverse of the testing machine 0.01mm/min. The loading process consisted of two cycles.

The first loading cycle — a smooth increase in the compressive load to 160 N followed by unloading — is necessary to detect AE pulses corresponding to the friction process of AOC structural elements.

The second loading cycle consists in a gradual rising of compressive load until the AE pulses are detected, the duration of which exceeds the value $t_i = 10\,000\,\mu$s. In paper [5], the authors found that occurrence of AE pulses with a duration of more than $10\,000\,\mu$s during mechanical quasi-static loading of a single crystal of paratellurite indicates irreversible changes in it associated with the formation of continuity defects.

After loading with these two cycles, the primary parameters of the detected AE signals were evaluated depending on the level of the applied load. Fig. 6 illustrates the dependencies of the amplitude (u_m) and duration (t_i) AE pulses with applied loading curve, where P — compression load, τ — time.

As shown in Fig. 6, *a, c*, when loading the AOC during the first cycle to $P = 23.4$ N ($\tau \leq 101.4$ s) AE pulses were not detected, indicating the absence of damage accumulation in both, the single crystal and AOC body. With a further increase in the applied load, AE pulses appeared, the maximum amplitude and duration of which reached values of 54.3 dB and $9360\,\mu$s, respectively. Such values of AE parameters are typical for the process of elastoplastic deformation of AOC body [17]. When the load was increased to $P = 160$ N, three AE pulses were detected, each of which in terms of its parameters is peculiar to elastic deformation of AOC metal.

During the second loading cycle as seen from Fig. 6, *b, d*, until the load reached $P = 10.2$ N 14 AE pulses had been detected. This phenomenon is caused by the Felicity effect, which consists in detecting AE pulses until the maximum load of the previous loading cycle is reached [18]. This effect is manifested during cyclic loading of a product that has defects, whereas for the defect-free materials and samples, the number of detected AE pulses during reloading will be extremely low or zero.

Further increase of the applied load up to $P = 147.4$ N resulted in detection of AE pulses with an amplitude and duration of 73.8 dB and $13\,542\,\mu$s, respectively. The detection of high-amplitude pulses of long duration is one of the criteria for identifying the process of friction of the sides of a developing crack in a single crystal of paratellurite. When $P = 276$ N was reached, the maximum amplitude and duration of the detected AE pulses reached values 84 dB and $23\,900\,\mu$s, respectively. A further increase in the applied load could lead to the appearance of a main crack and destruction of the single crystal, so the test was stopped.

According to the obtained primary characteristics of AE signals, — maximum amplitude and pulse duration — micro-damages were formed in the body of the paratellurite single crystal. In order to more reliably identify the processes of formation and development of micro-damages, the results of AE monitoring were processed using statistical analysis methods. The value of high-level quantile of the empirical functions (F_W^*) of pulse duration distribution was used as a numerical parameter. The empirical distribution functions were calculated using a sliding window of $W = 25$ pulses. Value of F_W^* function was calculated using the following formula:

$$F_W^*(y) = \frac{1}{W}\sum_{i=1}^{W} I(X_i < y), \tag{1}$$

where W — is sample size (window function size); I — number of AE parameters satisfying the condition $X_i < y$; X_i — value of AE parameter from the sample $X = (X_1, \ldots, X_i, \ldots, X_W)$; y — threshold value of AE parameter in the range $y \in [X_{\min}, \ldots, X_{\max}]$.

Figure 7 shows the dynamics of changes in the quantile values of $p = 0.85$ level of the empirical function of AE pulse duration distribution ($[t_i]_{p=0.85}$) for pulses detected during the second cycle of AOC compression loading.

At the initial loading stage ($P < 102$ N, $\tau < 36$ s) the value of criterion parameter is equal $[t_i]_{p=0.85} = 4037\,\mu$s. With the increase of applied load the parameter rises to $[t_i]_{p=0.85} = 13\,196\,\mu$s under the load of $P \approx 150$ N and loading time of $\tau \approx 41$ s, which indicates that friction process was initiated along the sides of the crack [5]. Thus, the use of the statistical parameter AE $[t_i]_{p=0.85}$ made it possible to determine the moment of crack formation in the single crystal of paratellurite located in AOC at the initial stage of damage accumulation.

3. Diagnostics of the single crystal of paratellurite by AE method under the influence of the temperature gradient

The third stage of the experiment consisted in the study of a single crystal of paratellurite by AE method under the influence of a temperature gradient. These experiments are relevant because of the occurrence of temperature gradients during operation of AO systems [19–21]. The appearance of temperature gradients in damaged materials can lead to the formation and development of defects in controlled products, which means that their performance characteristics deteriorate.

For the experiment, single crystals of paratellurite were extracted from the AOC body. The tests consisted of lowering the temperature of the controlled product to $-75\,^{\circ}$C, which is the lower limit of the climatic temperature range, followed by natural heating to room temperature. The single crystal in its initial state (before compression tests) and after growing the defect in the second stage of research (after

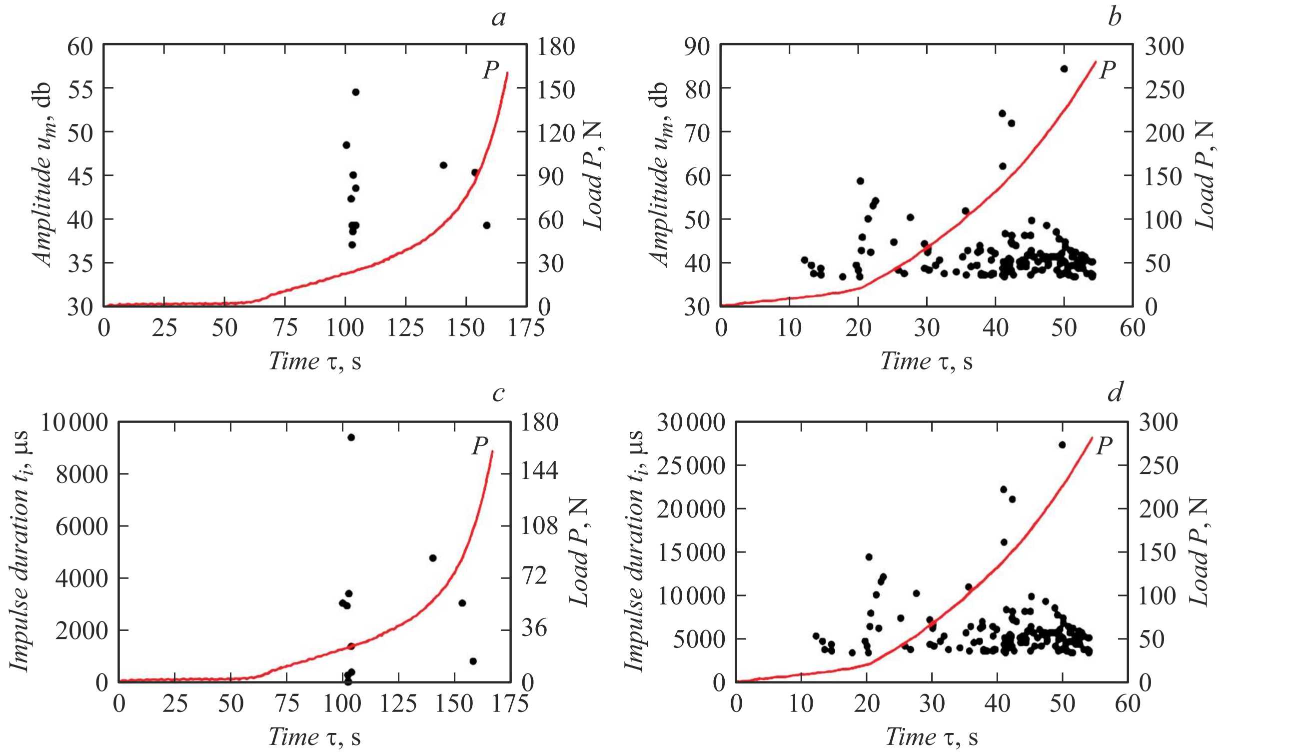

Figure 6. Dependencies of amplitude u_m (a, b) and duration t_i (c, d) of AE pulses detected in AOC compression at the first (a, c) and second (b, d) loading cycles (red lines indicate the loading curves, black marks — indicate the values of AE parameter).

compression tests) was cooled in a LaudaPro temperature room by immersion in liquid silicone oil cooled to $-75\,^\circ$C. After cooling, the single crystal was removed from the oil and placed through a layer of contact grease on the metal base of the testing machine with AET „VS150-RIC“ fixed on it. During natural heating of the single crystal from $-75\,^\circ$C to room temperature the occurring AE signals were continuously recorded. The dynamics of the temperature change of the single crystal was recorded using a pyrometer every 10 s. The results obtained were approximated using Newton's law of cooling and compared with the values of the amplitude and duration of the detected AE pulses. The results of comparing AE data generated in a single crystal in its initial state and with a pronounced defect are shown in Fig.8.

As shown in Fig. 8, *a, c*, with increasing temperature stresses in a defect-free single crystal, the amplitude and duration of the recorded AE pulses do not exceed the values 52.8 dB and 2553 μs, respectively. When heated to room temperature, there is a sharp decrease in the amplitude and duration of the recorded signals. This process may be caused by a decrease in the temperature deformations of the single crystal, leading to its friction against the surface of the acoustic waveguide.

The results of AE monitoring of the process of temperature deformations of a damaged single crystal indicate that there's a drastic change in the characteristics of the flow of detected signals. As can be seen from Fig. 8, *b, d*, total number of detected signals lowered from $N_\Sigma = 33$ to 7 AE

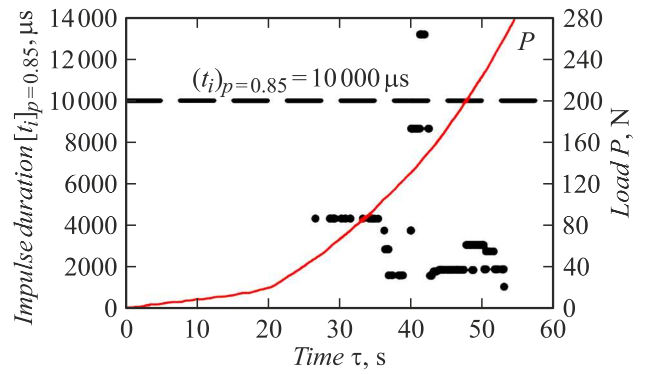

Figure 7. Progress of change of the criterion parameter $([t_i]_{p=0.85})$ under static compression of AOC with a single crystal of paratellurite with applied loading curve „load P — time τ„ (red line indicates the loading curve, black marks — indicate the values of criterion parameter $[t_i]_{p=0.85}$).

pulses, at that, maximal values of amplitude and duration grew up to 98.2 dB and 38 280 μs, respectively. A drastic change in the characteristics of the detected AE pulses is due to the process of relaxation of temperature stresses when the main crack starts to grow in the single crystal formed during the crystal heating (Fig. 9). Obviously, for the single crystal of TeO_2 with a crack previously detected by AE method, the presence of a temperature gradient proved to be sufficient for the rapid development of the

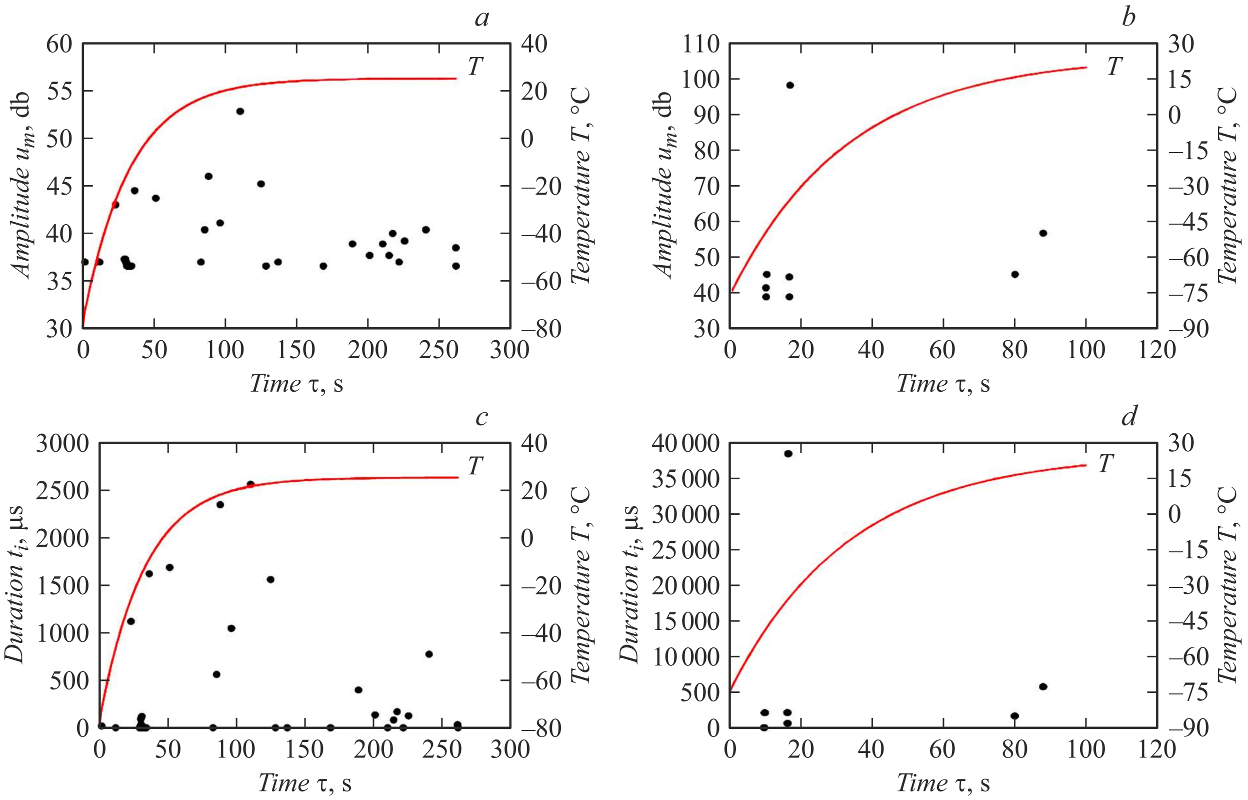

Figure 8. Dependencies of the amplitude u_m (a, b) and duration t_i (c, d) of AE pulses detected during heating of paratellurite single crystal in the original defect-free (a, c) and damaged (b, d) states.

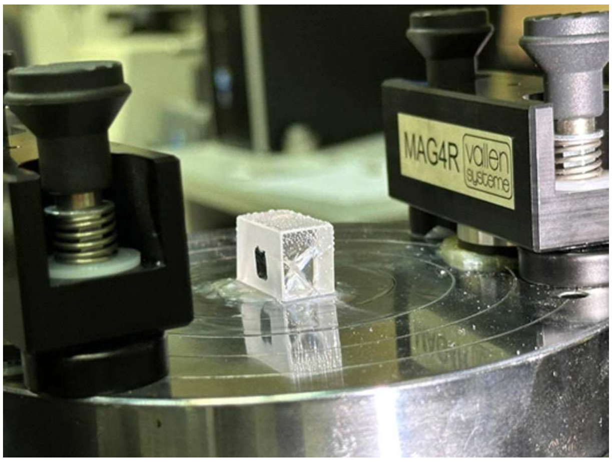

Figure 9. Formation of a main crack in a damaged paratellurite single crystal due to exposure to temperature stresses.

main crack. Under real conditions, a single crystal with such a defect leads to the failure of AOC.

To distinguish between AE sources of different origins, the spectral characteristics of acoustic signals detected during heating of a defect-free and damaged single crystal were calculated. The energy parameters of AE pulse spectra were calculated using the fast Fourier transform method, and their characteristic shapes are shown in Fig. 10.

Fig. 10, *a* shows the characteristic shape of AE pulses that occur when exposed to temperature stresses on a defect-free single crystal of paratellurite. The shape of such a pulse has a short rise time and a small amplitude. As illustrated in Fig. 10, *c*, the highest amplitude of the spectrum fundamental harmonics corresponds to the frequencies $f = 102$ and 150 kHz (quasi-resonant frequency of the receiving transducer). It should be noted that low-amplitude pulses with a characteristic low-frequency spectrum occur during the friction process [22]. Thus, the AE pulse shown in Fig. 10, a, can be attributed to the process of friction of a single crystal against the surface of the acoustic waveguide.

The AE pulse, which occurs during the action of temperature stresses on defective paratellurite single crystals, can be divided into two time intervals. A low-frequency signal characteristic of the friction process was detected in the time interval $t = 0{-}833\,\mu$s. At the moment of time $t = 834\,\mu$s, there is a drastic increase in the amplitude of AE pulse which is characteristic to formation of the main crack in brittle materials [23]. Due to the large amount of energy generated during relaxation of thermomechanical stresses, the appearance of local maxima of AE pulse is observed, e.g., at the moments of time $t = 1066$, 1372, $1644\,\mu$s, etc. The local maxima are detected due to the process of re-reflection of the acoustic wave from the surface of paratellurite single crystal. It should be stressed that the highest amplitude of harmonics of the spectrum shown in

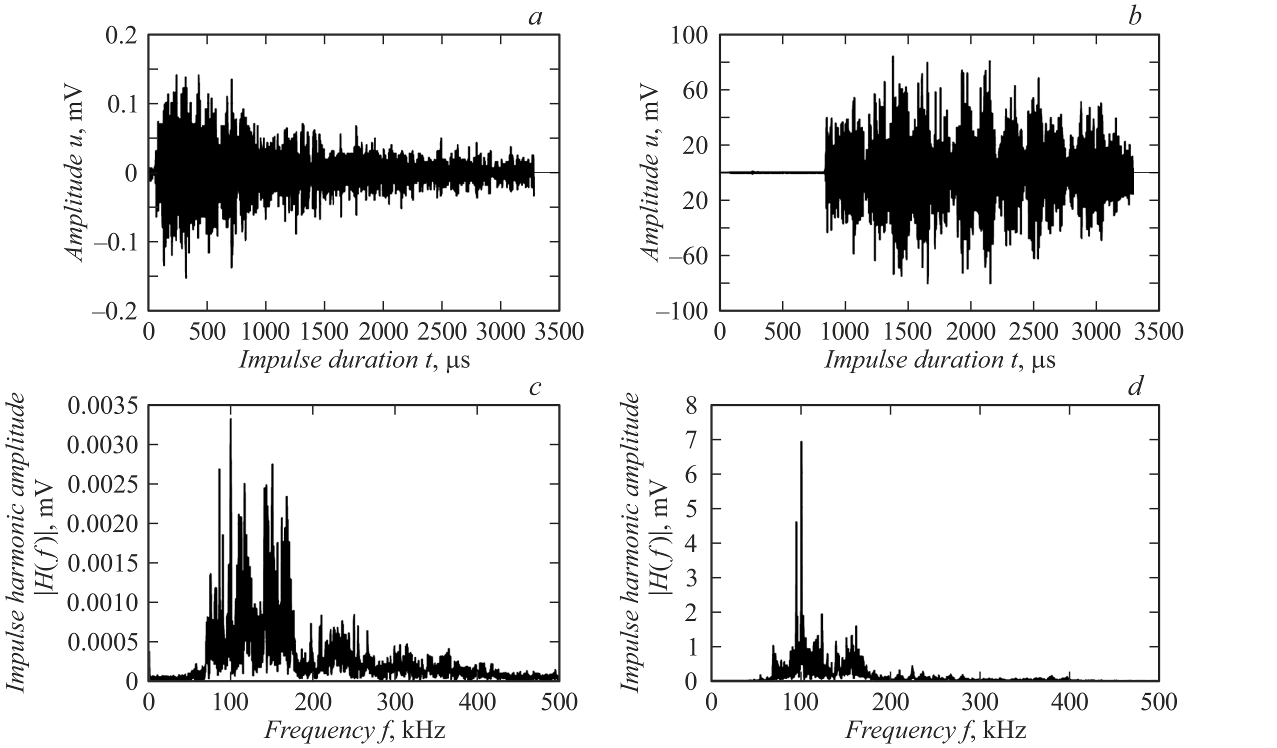

Figure 10. Characteristic shapes (a, b) and frequency spectra (c, d) of AE pulses detected when the defective (a, c) and non-defective (b, d) single crystal of paratellurite was exposed to the temperature stresses.

Fig. 10, d and corresponding to the frequency $f = 102$ kHz, increased from $|H(f)| = 0.003$ to 6.88 mV (i.e. by more than 3 orders of the magnitude). At that, the amplitude of AE pulse harmonic at frequency $f = 250$ kHz grew from $|H(f)| = 0.0007$ to 0.1 mV (i.e. by more than 2 orders of magnitude).

Thus, the ratio of the total harmonic amplitude of an acoustic signal in the frequency ranges $f = [50-150]$ kHz and $[200-300]$ kHz can be used as a numerical characteristic used to separate naturally different AE sources:

$$\rho = \sum_{f=50\,\text{kHz}}^{f=150\,\text{kHz}} |H(f)| \Bigg/ \sum_{f=200\,\text{kHz}}^{f=300\,\text{kHz}} |H(f)|, \qquad (2)$$

where $\sum_{f=50\,\text{kHz}}^{f=150\,\text{kHz}} |H(f)|$ — total amplitude of AE pulse spectrum harmonics in the frequency range $f = [50-150]$ kHz; $\sum_{f=200\,\text{kHz}}^{f=300\,\text{kHz}} |H(f)|$ — total amplitude of AE pulse spectrum harmonics in the frequency range $f = [200-300]$ kHz.

The result of segmentation according to the proposed criterion of ρ AE pulses detected in a defective single crystal during its heating is shown graphically in Fig. 11. The figure illustrates separation of acoustic signals into two segments corresponding to the processes of friction (I) and growth of the main crack (II) in the single crystal of paratellurite, according to the amplitude and relative variation of the total amplitude of the spectrum of detected AE pulses in the frequency range $f = [50-150]$ kHz and $[200-300]$ kHz.

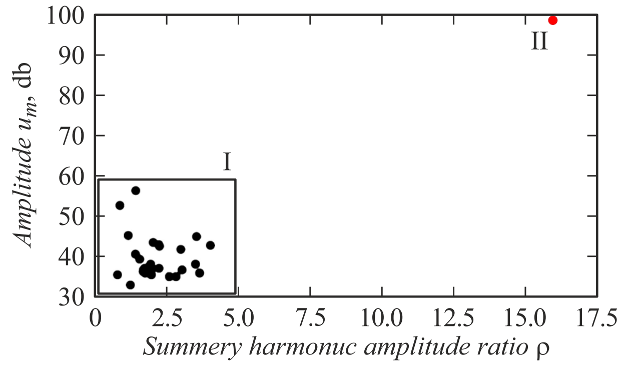

Figure 11. Segmentation of AE pulses corresponding to the processes of friction (I) and main crack development (II) in the single crystal of paratellurite.

As mentioned earlier, the friction process is characterized by low-amplitude signals with a uniform spectrum in the region of 50–150 kHz. In this regard, the boundaries of segment I corresponded to the ranges $u_m = 30-60$ dB and $\rho = 0.01-5$. For AE pulses corresponding to the process of formation and growth of the main crack in paratellurite crystal, the maximum value of the parameter ρ increased from 3.98 to 15.49. Thus, based on the results of spectral analysis of AE pulses that occur during exposure to temperature stresses, a qualitative assessment of the integrity of paratellurite single crystal is viable.

Conclusion

The paper considers the possibilities of AE monitoring of the process of damage accumulation in a single crystal of TeO_2 exposed to mechanical and thermal stresses. For the first time, the AE diagnostics of a real acousto-optic cell used in tunable spectral filters has been performed.

It was found that excitation of high-frequency ultrasonic signals in a single crystal of paratellurite during its operation does not affect the AE monitoring results, which is confirmed by the similarity of noise signals histograms in the presence and absence of high-frequency signals in the operating frequency range $f_{ae} = 27-60$ MHz.

According to the results of static compression of an acousto-optic cell consisting of two loading cycles, the characteristic parameters of AE pulses are determined. During the first loading cycle, it was found that the amplitude and duration of AE pulses recorded during deformation of the aluminum body did not exceed the values of 54.3 dB and 9360 μs. During the second loading cycle, the moment of crack initiation in the single crystal of paratellurite was determined based on the maximum values of the amplitude and duration of the detected AE pulses. The quantile value of the empirical AE pulse duration distribution function was used as a numerical criterion. The moment of formation of irreversible damages in the single crystal of paratellurite during loading is determined by the value of $[t_i]_{p=0.85} > 10\,000\,\mu$s.

At the final stage of the experiments, the single crystal of paratellurite was studied by AE method under the influence of a temperature gradient. The spectral characteristics of AE pulses detected during exposure to temperature stresses are compared for a defect-free single crystal and a crystal with a defect. A numerical criterion for the damage of the paratellurite single crystal is proposed based on calculating the ratio of the total harmonic amplitudes of an acoustic signal in the frequency ranges $f = 50-150$ kHz and $200-300$ kHz.

Based on the findings, an algorithm for monitoring an acousto-optic cell using the AE method is proposed, consisting in mechanically loading the cell, followed by calculating the high-level quantile of the empirical duration distribution function $[t_i]_{p=0.85}$ and the ratio ρ of the total harmonic amplitude of AE pulse spectrum in the frequency range $f = 50-150$ kHz and $200-300$ kHz. The proposed approach makes it possible to determine the actual state of TeO_2 single crystal under the impact of mechanical stresses. A further progress of the proposed technique includes development of algorithms for the early diagnostics of damage accumulation in the single crystal of paratellurite based on the results of extrapolation of parameters ρ and $[t_i]_{p=0.85}$.

In the future, it seems promising to use complex research methods based on simultaneous application of several experimental methods to study a single sample — the broadband video spectrometry, AE and X-ray diffractometry. In the future, such methods will make it possible to conduct research on ready-made devices in conditions close to real operating conditions.

Funding

This study was carried out with the financial support of the Ministry of Science and Higher Education of the Russian Federation under the Agreement No.075-15-2024-637 dated June 28, 2024

Conflict of interest

The authors declare that they have no conflict of interest.

References

[1] V.V. Dmitriev, G. Gurzadyan, D.N. Nikogosyan. *HandBook of nonlinear optical crystals* (Springer, 1991)

[2] A. Bain. *Crystal Optics: Properties and Applications* (Wiley, 2019)

[3] H.S. Bagdasarov, E.I. Givargizov, L.N. Demyanets, V.A. Kuznetsov, A.N. Lobachev, A.A. Chernov. *Sovremennaya kristallografiya. Obrazovaniye kristallov* (M. Nauka, 1980), v. 3 (in Russain).

[4] V.I. Ivanov, V.A. Barat. *Akustiko-emissionnaya diagnostika* (Spektr, M., 2017) (in Russian).

[5] A.S. Machikhin, D.V. Chernov, A.Yu. Marchenkov, Ya.A. Eliovich, V.I. Akkuratov, A.A. Pankina, A.A. Khvostov. FTT, **65** (11), 2000 (2023) (in Russian). DOI: 10.21883/FTT.2023.11.56556.148

[6] N. Uchida. Phys. Rev. B, **4**, 3736 (1971). DOI: 10.1103/PhysRevB.4.3736

[7] A.P. Goutzoulis, V.V. Kludzin. *Design and Fabrication of Acousto-Optic Devices* (CRC Press, Boca Raton, 1994)

[8] A. Vinogradov, I.S. Yasnikov. Acta Mater., **70**, 8 (2014). DOI: 10.1016/j.actamat.2014.02.007

[9] Z.G. Dong, H. Huang, R.K. Kang. Adv. Mater. Res., **76–78**, 404 (2009). DOI: 10.4028/www.scientific.net/AMR.76-78.404

[10] Y.T. Wong, P. Wright, M.E. Aulton. Drug Dev. Ind. Pharm., **14** (15–17), 2109 (1988).

[11] D. Drozdenko, J. Bohlen, F. Chmelík, P. Lukáč, P. Dobroň. Mater. Sci. Eng. A, **650**, 20 (2016). DOI: 10.1016/j.msea.2015.10.033

[12] T.L. Zoltán, L. Daróczi, E. Panchenko, Y. Chumlyakov, D.L. Beke. Materials, **13** (9), 2174 (2020). DOI: 10.3390/ma13092174

[13] A. Weidner, A. Vinogradov, M. Vollmer, Ph. Krooß, M.J. Kriegel, V. Klemm, Yu. Chumlyakov, T. Niendorf, H. Biermann. Acta Mater., **220**, 117333 (2021). DOI: 10.1016/j.actamat.2021.117333

[14] L. Daróczi, T.Y. Elrasasi, T. Arjmandabasi, L.Z. Tóth, B. Veres, D.L. Beke. Materials, **15** (1), 224 (2022). DOI: 10.3390/ma15010224

[15] A. Machikhin, D. Chernov, D. Khokhlov, A. Marchenkov, A. Bykov, Y. Eliovich, I. Petrov, T. Balandin, A. Kren, I. Sergeev, Y. Pisarevsky. Materials, **17** (14), 3590 (2024). DOI: 10.3390/ma17143590

[16] V.I. Batshev, A.S. Machikhin, A.B. Kozlov, S.V. Boritko, M.O. Sharikova, A.V. Karandin, V.E. Pozhar, V.A. Lomonov. J. Commun. Technol. Electron., **65** (7), 800 (2020). DOI: 10.1134/S1064226920070025
[17] A.A. Dmitriev, V.V. Polyakov, A.A. Lependin. Pisma o materialakh **8** (1), 33 (2018) (in Russian). DOI: 10.22226/2410-3535-2018-1-33-36
[18] Y. Sun, F. Yu, J. Lu. Lithosphere, **2023** (1), 2773795 (2023). DOI: 10.2113/2023/2773795
[19] S.N. Mantsevich, E.I. Kostyleva. Ultrasonics, **91**, 45 (2019). DOI: 10.1016/j.ultras.2018.07.016
[20] S.N. Mantsevich, O.I. Korablev, Yu.K. Kalinnikov, A.Yu. Ivanov, A.V. Kiselev. Acta Phys. Polonica A, **127** (1), 43 (2015). DOI: 10.12693/APhysPolA.127.43
[21] S. Tretiakov, A. Kolesnikov, I. Kaplunov, R. Grechishkin, K. Yushkov, E. Shmeleva. Intern. J. Thermophys., **37** (1), Art. Num. 6 (2016). DOI: 10.1007/s10765-015-2017
[22] S.A. Dobrynin, E.A. Kolubaev, A.Yu. Smolin, A.I. Dmitriev, S.G. Psakhye. Pis'ma v ZhTF **36**, (13), 47 (2010) (in Russian).
[23] D. Triantis, I. Stavrakas, E.D. Pasiou, S.K. Kourkoulis. Forces in Mechanics, **15**, 100265 (2024). DOI: 10.1016/j.finmec.2024.100265

Translated by T.Zorina