Materials Physics and Mechanics. 2022;48(2): 208-216
Research article
http://dx.doi.org/10.18149/MPM.4822022_6

Received: December 10, 2021
Accepted: March 29, 2022

UNSTABLE PLASTIC FLOW IN STRUCTURAL MATERIALS: TIME SERIES FOR ANALYSIS OF EXPERIMENTAL DATA

Vladislav K. Kazankov[1], Anna G. Shmeleva[2], Ekaterina V. Zaitseva[1]✉

[1]ITMO University – Kronverksky Prospekt 49, bldg. A, Saint Petersburg, 197101, Russia

[2]MIREA – Russian Technological University, 78 Vernadsky Avenue, Moscow 119454, Russia

✉ zaytskaterina@gmail.com

Abstract. The present study provides the mathematical description of changing metals characteristics during exploitation, as well as identifies behaviors and features during plastic deformation. Modern experimental facilities allow conducting a full-scale experiment, recording the effects observed, determining the patterns of materials behavior of and their alloys to predict the occurrence of unstable plastic flow. The arrays of experimental data obtained in the format of discrete values were processed with the wave-record method for the data interpolation and normalization. The results' comparison enabled to determine the class of materials with similar patterns of deformational plastic behavior. That allowed us to describe the patterns of irreversible deformations and their nature to formulate the postulates for the theory of plasticity, materials science, and prediction of complex systems' behavior. The paper presents the results of experimental studies of plastic deformation of aluminum alloy samples to determine the characteristics of unstable plastic flow in the material. The analysis of the obtained data for the samples confirmed the presence of the Portevin-Le Chatelier effect. Based on the experimental results, deformation diagrams and time series were developed, and the data correlation for the samples was also confirmed. The wave process that occurs in the material during stretching correlates hydrodynamic with the occurrence of rogue waves. It is important to note that when analyzing the time series of experimental data for aluminum alloys, a pattern of correspondence with time series in the analysis of rogue waves was noted.

Keywords: Portevin-Le Chatelier effect, aluminum alloys, deformation diagrams, plasticity, time series, rogue waves

***Acknowledgements**. No external funding has been received for this study.*

Citation: Kazankov VK, Shmeleva AG, Zaitseva EV. Unstable plastic flow in structural materials: time series for analysis of experimental data. *Materials Physics and Mechanics.* 2022;48(2): 208-216. DOI: 10.18149/MPM.4822022_6.

1. Introduction

Aluminum and its alloys are used in industry due to their lightness, corrosion resistance, and malleability to stamping. However, aluminum alloys exhibit plastic flow instability, known as the Portevin-Le Chatelier effect. For practical purposes, this effect causes the localization of dislocations and appearance of deformation bands such as Chernov-Luders bands [1]. This effect results in material structure violation and surface roughness appearance. As metals and alloys are widely used in the food, pharmaceutical, and automotive industries, where any irregularities on the surface are unacceptable, the issue of determining the boundaries separating the areas of stable and unstable plastic flow is acute.

The Portevin-Le Chatelier effect influences most properties of materials. It increases the yield stress, the tensile strength, and the hardening rate of materials. Therefore, the ductility of metals reduces with a corresponding elongation, which decreases the effective cross-sectional area. Alloys under load become susceptible to service failures because of a decrease in viscosity [2,3]. The combination of negative qualities caused by the Portevin-Le Chatelier effect with environmental factors weakening the material leads to early wear of the material. Further embrittlement of the material may be caused by the presence of hydrogen in gaseous and aqueous media, which accelerate corrosion processes, or by physical contact of the bearing materials with other materials, which leads to localized corrosion. Thus, for structural materials, the detection of susceptibility to the Portevin-Le Chatelier effect is one of the key tasks.

The Portevin-Le Chatelier effect is worth both experimental study and theoretical analysis, as well as establishing the stability loss criterion for plastic deformation and determining the instability area [4]. However, the Portevin-Le Chatelier effect has not been sufficiently studied experimentally, despite its broad theoretical basis and widespread use of alloys in industry. As part of this work, we studied the behavior of metals and alloys characteristics by conducting an experiment on the rupture of parts and considering the results obtained. The purpose of this work is to demonstrate a method for analyzing the dynamics of material rupture through the interpretation of experimental data in the time series format. The authors propose to investigate time series in a similar way to the methods of studying hydrodynamic processes of rogue waves.

Rogue waves occur in various physical processes. In addition to the direct appearance of waves in the ocean [5] and in laboratory experiments, they occur in optical systems [6], as well as in plasma physics, condensed matter physics and Bose-Einstein condensate [7,8]. Such a frequent occurrence of rogue waves in various physical systems suggests that the set of processes containing them may be wider. For example, researchers observe the occurrence of similar processes in materials science, in metamaterials [9,10]. In this paper, it is proposed to begin studying the properties of materials using the methodology of the study of rogue waves.

2. Methodology

To study the effect of Portevin-Le Chatelier, metal parts were subjected to rupture on the installation. In the experiment, flat samples of a carbonized aluminum alloy with impurity content of no more than 0.5 percent were used. Sample parameters: length 0.12 m, width 0.015 m, thickness 0.003 m. The maximum size deviation is ± 0.0006 m. The appearance of the parts is shown in Figure 1. To study the effect of Portevin-Le Chatelier, metal parts were subjected to rupture on the installation. In the experiment, flat samples of a carbonized aluminum alloy with impurity content of no more than 0.5 percent were used. The appearance of the parts is shown in Fig. 1.

Each of the aluminum samples was subjected to rupture at the installation with the highest limit load of 5 kN and a measurement range of 0.3-5 kN. During the experiment, the internal stress of the sample and its stretching were recorded. Stretching was carried out at a constant speed (0.000018 m/s), so the time of the experiment turned out to be linearly dependent on stretching. This approach allows us to consider the relationship between the stretching of the sample and the internal stress through time series.

Figure 2 provides the visualization of the experimental results for one of the aluminum alloy samples. The dataset with experimental data is shown in [10].

Fig. 1. Samples

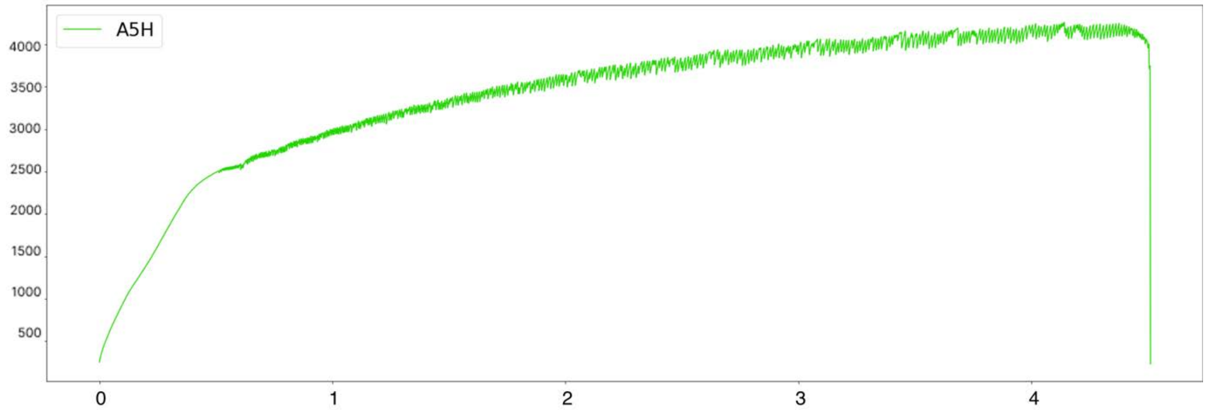


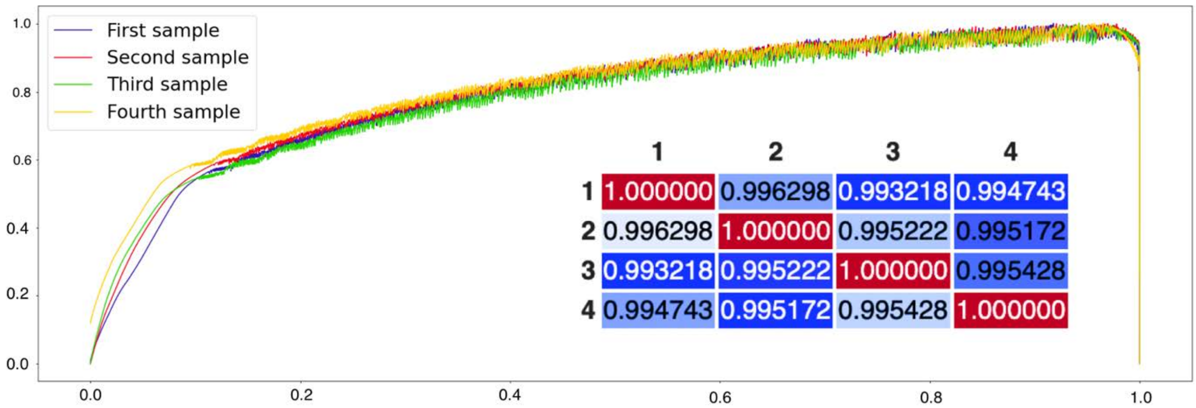
Fig. 2. The dependence of the stress on the stretching of the samples. The y-axis is the tension in kN, the x-axis is the time in seconds

Preprocessing of experimental data for all aluminum samples consists of three stages: interpolation, linear normalization, intervals allocation of the Portevin-Le Chatelier effect occurrence.

A program written in Python was developed to study the properties of alloys. The program structure consists of three stages.

At the first stage, experimental data is selected with a minimum number of rows. The minimum number of rows is the interpolation parameter for the remaining samples and corresponds to the total size of all datasets of the same material after interpolation.

Then, the experimental data is linearly normalized, and a correlation matrix is calculated for them; it allows confirming that all samples behave the same way. The result is shown in Fig. 3.



	1	2	3	4
1	1.000000	0.996298	0.993218	0.994743
2	0.996298	1.000000	0.995222	0.995172
3	0.993218	0.995222	1.000000	0.995428
4	0.994743	0.995172	0.995428	1.000000

Fig. 3. Experimental data on the tension-time dependence of aluminum alloy samples. The y-axis is the tension in kN, the x-axis is the time in seconds

At the last stage of preprocessing for each data set, the moment of the Portevin-Le Chatelier effect occurrence is located, and then all transformations in the study are carried out exclusively from this point in time until the sample breaks. By the moment fluctuations occur, we mean the moment of reaching the first local maximum from the beginning of the experiment.

Methods of time series analysis that allow to identify patterns, build forecasts, and develop models describing the characteristics of the behavior of the object of study in various fields of science [12,13]. The paper [12] describes research directions in the field of analysis and modeling of dynamics of time series of processes in complex systems. At work [6] methods of comparison of algorithms for processing time series are presented, the effectiveness of their application for building practical models and conducting scientific experiments is confirmed. It is noted that the processes considered in practice-oriented studies are extremely rarely stationary, therefore, methods of transition to stationary mathematical models are being developed, for example, the selection and removal of trend, noise, and periodic components from the time series.

The resulting preprocessed datasets can be interpreted as a time series. Wave height h_i of time series X_t is calculated using the following formula

$$h_i = x_{max} - (x_{minL} + x_{minR})/2,$$

where x_{max} is the local maximum, and x_{minL}, x_{minR} are the nearest local minima surrounding x_{max}. To construct the wave height distribution, it is necessary to introduce the concept of the wave equivalence class $[h]$. We assume that h_i is equivalent to if the following relation holds

$$round\left(\frac{h_i}{\delta}\right) = round\left(\frac{h_j}{\delta}\right),$$

where δ is the width parameter of the equivalence class. Figures 4-7 show the wave height distributions for one of the aluminum samples at different δ.

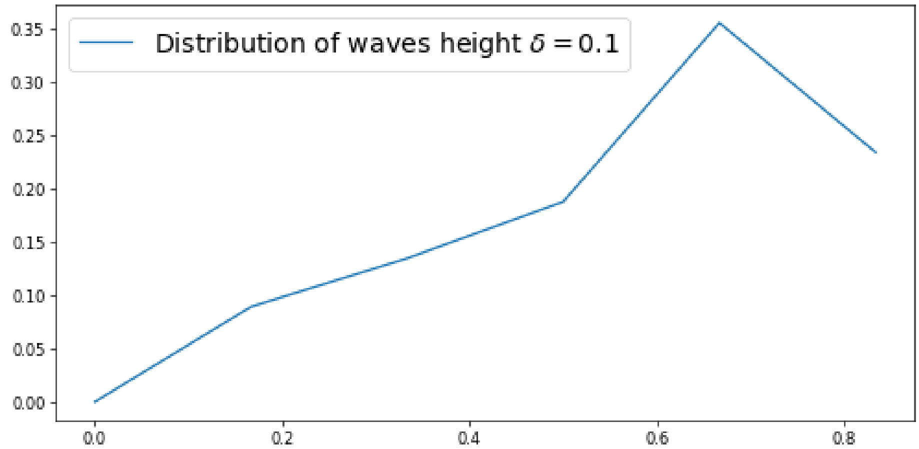


Fig. 4. Graph of the dependence of the wave height distribution on the stretching for a sample with $\delta = 0.1$ (on the y-axis, the normalized number of waves in the equivalence class, on the x-axis, the normalized wave heights)

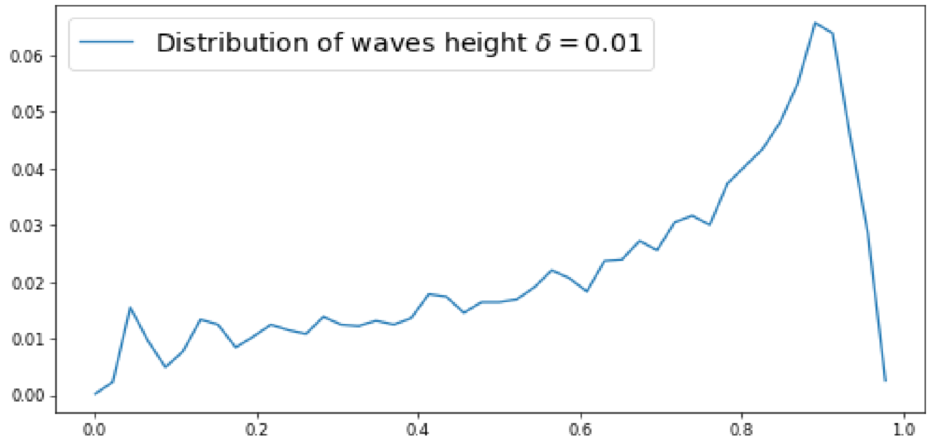


Fig. 5. Graph of the dependence of the wave height distribution on the stretching for a sample with $\delta = 0.01$ (on the y-axis, the normalized number of waves in the equivalence class, on the x-axis, the normalized wave heights)

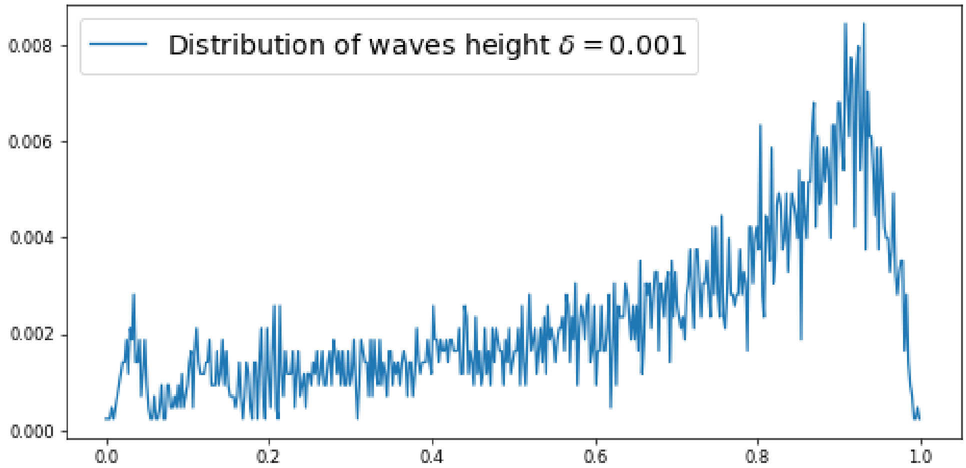


Fig. 6. Graph of the dependence of the wave height distribution on the stretching for a sample with $\delta = 0.001$ (on the y-axis, the normalized number of waves in the equivalence class, on the x-axis, the normalized wave heights)

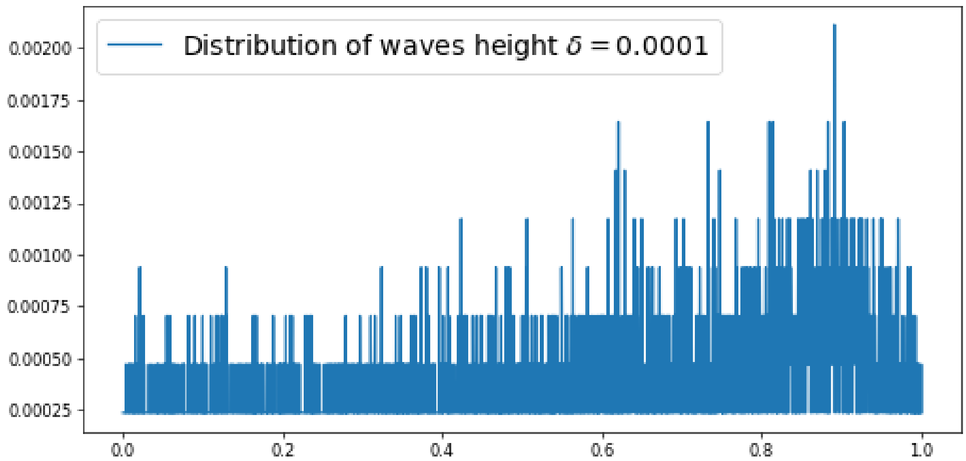


Fig. 7. Graph of the dependence of the wave height distribution on the stretching for a sample with $\delta = 0.001$ (on the y-axis, the normalized number of waves in the equivalence class, on the x-axis, the normalized wave heights)

When constructing the distributions, the number of unique wave height equivalence classes was found, then the number of class representatives was calculated. The equivalence classes linearly normalized from 0 to 1 are located along the horizontal axis. On the vertical axis, the number of classes encountered was normalized so that the number of all values of each class encountered equals one. Due to this approach, the resulting figures correspond to the density of the wave height distribution, if we consider the result of the experiment as a random process. The distribution profile resembles a beta distribution with parameters $a = 18, b = 4$, or the sum of an exponent with a damped harmonic closer to the maximum value of the distribution.

With a decrease in the value of parameter δ, the number of equivalence classes $[h]$ increases, with $\delta << 1e - 6$, the distribution is almost uniformly distributed over the segment $[0,1]$. The most informative picture is obtained at $\delta = 0.01$.This value is used later.

In [13], a study of dynamical systems was carried out, using the example of a hydrodynamic process, in the modeling of which random variables were generated based on functions with an exponential profile. It was noticed that the obtained simulation results correspond to the results of computational experiments [14,15]. The revealed pattern in the experimental data allows considering the hypothesis of the rogue waves existence in systems with the Portevin-Le Chatelier effect [16,17]. By a rogue wave, we mean a wave with amplitude criterion $H \geq 2.1$calculated by the following formula

$$H = \frac{h_i}{h_{sm}},$$

where h_i is the height of the wave with number i, and h_{sm} is the average height of one-third of the highest waves.

To reduce the values of the noise contribution to the data, we consider the standard deviation among n waves, denote this value by μ_n. Then, for the first $n - 1$ waves, $\mu_n = 0$. Then, in one conventional unit of time, there is a shift by one wave. Thus, for $n \in [4,100]$, a set of trajectories $\mu_n(t)$ is obtained. Among the whole set, we select trajectories based on the following criteria:

1. Rogue waves should occur among the estimates $\mu_n(t)$;
2. The number of rogue waves should not be less than twenty and exceed one hundred pieces;
3. Rogue waves should occur with some frequency.

The second criterion is consistent with the data obtained because of computational experiments [8,9], in which the number of rogue waves reached 25 pieces. The third criterion can be interpreted through the estimates $\mu_n(t)$, minimizing the average value of the estimates at each time.

Figure 8 shows the dependence of the change in estimate $\mu_n(t)$ on time, while among other estimates it was minimal, according to the second criterion. The red dots in the figure indicate the registered rogue waves. It can be noticed that after the last recorded rogue wave, the average value begins to decrease up to the rupture of the sample.

A similar dynamic was observed when modeling the hydrodynamic process [13] and when applying a similar technique for processing the results of a computational experiment [8,9].

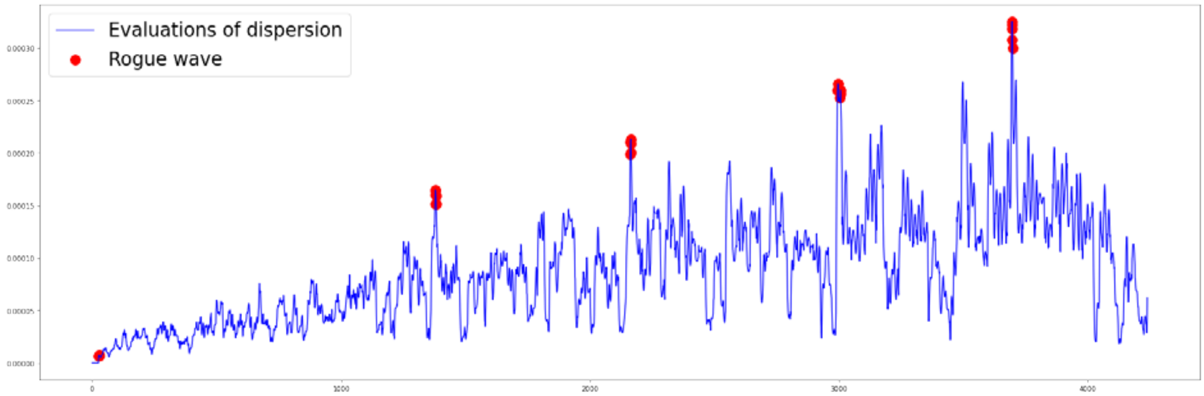


Fig. 8. Evaluation of an aluminum sample at $n = 26$ (on the y-axis, the value of the standard deviation μ_n; on the x-axis, standard units of time)

3. Results

Stretching experiments have been carried out for an aluminum alloy. The Portevin-Le Chatelier effect is registered on each sample. The technique for analyzing the Portevin-Le Chatelier effect has been developed based on the interpretation of experimental results as a time series. Wave height distributions are plotted for each sample. It is noted that when the global maximum for $\mu_n(t)$ is reached, a further decrease is observed in the average value of the estimate for the dispersion of wave heights.

4. Discussion

This paper considers the approach to studying the characteristics of the aluminum alloy during deformation and rupture. The authors apply time series analysis methods to study the Portevin-Le Chatelier effect. During the processing of experimental data, it was found that the obtained graphs reflect the process of the emergence of rogue waves.

The similarity of the distribution graphs for rogue waves and the processes of metal rupture can be explained using concentrations. If we consider the hypothesis that rogue waves arise due to a local concentration of energy, then a similar mechanism for alloys is the concentration of dislocations in materials.

5. Conclusion

The comparison of numerical processing of experimental data for alloys and liquids promises the use of waveforms for research in metallurgy. Considering the processes in alloys and liquids from the point of view of time series theory allows us to obtain identical distribution graphs. This fact makes further investigation of the Portevin-Le Chatelier effect crucial from the perspective of the theory of random processes. Moreover, it is necessary to study the reverse mechanism to reveal if there is an analog of the Portevin-Le Chatelier effect for liquids when a rogue wave appears. A positive answer to this question will allow dentifying the zones of stable and unstable behavior of waves. This will help create methods for predicting the appearance of a rogue wave.

References

[1] Zuev LB. Chernov–Luders deformations and Portevin–Le Chatelier in active deformable medium of various nature. *Journal of Applied Mechanics and Technical Physics*. 2017;2: 164-171.

[2] Brindley BJ, Worthington PJ. Yield-point phenomena in substitutional alloys. *Metallurgical Reviews.* 1970; 45(2): 101-114.

[3] Robinson JM, Shaw MP. Microstructural and mechanical influences on dynamic strain aging phenomena. *International Materials Reviews.* 1994;39(3): 113-122.
[4] Franklin S, Mertens F, Marder M. Portevin–Le Chatelier effect. *Physical review. E, Statistical physics, plasmas, fluids, and related interdisciplinary topics*. 2001;62: 206.
[5] Xiaoyu W, Tian B, Liu L, Sun Y. Rogue waves for a variable-coefficient Kadomtsev–Petviashvili equation in fluid mechanics. *Computers & Mathematics with Applications*. 2018;76(2): 215-223.
[6] Gao L, Wu Q, Cao Y, Wabnitz S, Zhu T. Optical polarization rogue waves and their identifications. *Journal of Physics: Photonics*. 2020;2(3): 032004.
[7] Chowdury A, Chang W. Rogue wave fission. *Physics Review Research.* 2021;3(3): 32-60.
[8] Li S, Li P, Gino B, Gino B. Solitons and rogue waves in spinor Bose-Einstein condensates. *Physical Review.* 2018;97: 220-221.
[9] Yasuhiro M, Hiromi Y, Jinkyu Y. Feasibility study on the formation of rogue waves in origami-based mechanical metamaterials. In: *Health Monitoring of Structural and Biological Systems XIV*. 2020. p.33.
[10] Zaitseva E. *The results of the experiment on the stretching of aluminum alloy samples*. Available from: https://github.com/zaytskaterina/experiment-with-stretching (accessed 27 March 2022).
[11] Alaei E, Marks B, Einav I. A hydrodynamic-plastic formulation for modelling sand using a minimal set of parameters. *Journal of the Mechanics and Physics of Solids*. 2021;151: 104388.
[12] Andrianova EG, Golovin SA, Zykov SV, Lesko SA, Chukalina ER. Review of modern models and methods of analysis of time series of dynamics of processes in social, economic, and socio-technical systems. *Russian Technological Journal.* 2020;8(4): 7-45.
[13] Kalugin TR, Kim AK, Petrusevich DA. Analysis of the high order ADL(p, q) models used to describe connections between time series. *Russian Technological Journal.* 2020;8(2): 7-22.
[14] Shkunkov A, Zaitseva E, Kazankov V. Modeling, and information theory. In: *The fifth scientific and technical conference of students and postgraduates of MIREA - Russian Technological University: Proceedings*. 2020. p.446-450.
[15] Shami R, Yudin A. Simulation of spatiotemporal spread of rogue waves. *Doklady Earth Sciences.* 2013;448(20): 240-242.
[16] Shamin RV, Gorlenko AV, Smirnova A. On the stability of rogue waves. *Computational Technologies*. 2012;18(1): 96-105.
[17] Kurkin AA, Pelinovsky EN. *Rogue waves: facts, theory, and modeling.* 1st ed. Berlin; 2016.

THE AUTHORS

Zaitseva E.V.
e-mail: zaytskaterina@gmail.com
ORCID: 0000-0003-3982-3592

Shmeleva A.G.
e-mail: ann_shmeleva@mail.ru
ORCID: 0000-0003-2300-3522

Kazankov V.K.
e-mail: v.kazankov98@gmail.com
ORCID: 0000-0002-7766-7730