

## Digital method for analysing speckle-interferometric images of material deformation

Valeriy V. Bodryshev<sup>1</sup>, Arseniy V. Babaytsev<sup>2</sup>, Alexander A. Orekhov<sup>2</sup>, Yan Naing Min<sup>3</sup>

<sup>1</sup> Department of Engineering Graphics, Moscow Aviation Institute (National Research University)

<sup>2</sup> Institute of General Engineering Training, Moscow Aviation Institute (National Research University)

<sup>3</sup> Department of Mathematics, Defence Services Academy

### ABSTRACT

Residual stresses arising from the technological processes of manufacturing aircraft structures can considerably affect the bearing capacity of the structure, which justifies the need to assess the level of these stresses. The study analysed the speckle interferometric images in terms of the parameter image intensity. This method allows assessing the picture of the change in this parameter both in a particular band, and performing a comparative analysis in a number of bands. Due to the presence of a correlation between the material deformation and the intensity of the image, the dynamics of the variation of the stress state (residual stresses) is estimated. When decoding the holograms, the authors used the Aleksandrov-Bonch-Bruevich vector equation. Double exposure of speckle holograms was applied and photo processing of the hologram was performed. It is shown that, depending on the position of the beam from the hole, there is a change in the image intensity. It was proved that the method employed in the study does not depend on external factors. The proposed approach allows taking a fresh look at the picture of stress state analysis and evaluating the qualitative and quantitative processes in the deformation zone, namely around the drilled hole in the plate.

**Keywords:** Image intensity, Digital processing, Shadow images, Speckle holography, Residual stresses.

### Corresponding Author:

Valeriy V. Bodryshev  
Department of Engineering Graphics  
Moscow Aviation Institute (National Research University)  
125993, 4 Volokolamskoe Shosse, Moscow, Russian Federation  
E-mail: vv\_bodryshev7016@nuos.pro

### 1. Introduction

In composites currently used in aircraft structures, as a result of manufacturing processes, residual stresses occur rather frequently, which can considerably affect the bearing capacity of the structure [1-11]. This is especially important for composite structures with various nanomodifications [12]. As a consequence, it is extremely important to assess the level of these stresses. In these studies, a method for determining residual stresses in orthotropic composite plates made of various materials in spatiotemporal observation [13] was developed and verified, based on the measurement of local displacements by the method of electron speckle interferometry. In [14; 15], the analysis of the stress state in plates with holes of different diameters was analysed in minute detail.

The study [16] developed and approbated a new method for determining the main components of residual stresses in composite plates. It is based on through-hole drilling and further measurements of hole diameter increments in the main stress directions using electron speckle interferometry. The theoretical and metrological foundations of the approach follow from the analytical solution of S.G. Lekhnitskiy, describing the stress concentration along the edge of the central open hole in a rectangular orthotropic plate under tension

in the main directions of anisotropy.

In [17-23], a new experimental method was presented for determining the parameters of both singular and non-singular fracture mechanics using a modified version of the crack compliance method. Its essence lies in measuring the local deformation response in terms of displacements at a small increment in the crack length by the method of electron speckle interferometry. Studies [24-27] presented the speckle-interferometry analysis of the stress-strain state around the hole at the stages of loading up to fracture. Methods of off-bench registration and decoding of speckle holograms were proposed for measuring individual plane and bending normal spatial components of deformations and displacements of full-scale structures when tested in industrial conditions. Study [28] presented the results of deformation of a sample with different hole sizes. Paper [9] described a simple technique for measuring the elastic moduli and Poisson's ratio.

The papers used in this study contributed to a detailed analysis of the operational parameters of the investigated design solutions. It is believed that the technical parameters of materials are determined by interference fringes, which constitute the locus of points of equal displacement during deformation. The sensitivity of the interferometric bands significantly differs in various components of the strain tensor. For example, when sufficiently thick specimens are stretched, flat components are observed in the interferograms, and when thin specimens are stretched, materials bending out of the plane of deformation are observed.

In this paper, to study such problems, it was proposed to apply a digital method of processing photographs by the parameter intensity (brightness) of images. This parameter was used to investigate the microstructure and surface of materials upon mechanical deformation tests [29-35]. Study [13] demonstrated that the quantitative composition of the material structure can be estimated by a given parameter. There is also a correlation between the intensity of the image and the surface roughness of the product [36]. Investigation of micrographs of polymer nanoparticles by the parameter of image intensity allows accurately identifying the shape and size of particles, the dynamics of the polymer deposition under study [37].

By analysing speckle-interferometric images in detail, considering the dynamics of the change in the image intensity, one can analyse its change both in a separate band, in a number of adjacent bands, and presented in different images. For example, when analysing the stress state with different hole diameters or with different composite materials. This method allows for a deeper understanding of the deformation processes of the material, because there is certainly a correlation between material deformation (shear) and the intensity of the images. Various tasks related to material deformation are described in [38-41].

## 2. Material and Methods

At present, when decoding holograms, the vector equation of Aleksandrov-Bonch-Bruevich is mainly used [42].

$$\vec{U}(\vec{\rho}_i - \vec{\rho}_o) = \lambda n, \quad (1)$$

where  $U$  is the vector of displacement of the point of the object,  $\rho_i, \rho_o$  are the vectors of illumination and observation,  $\lambda$  is the laser wavelength,  $n$  is the order of bands.

In this equation, the vectors of displacements of the points of the object recorded on the holographic interferogram are associated with the vectors of illumination and observation, which explain the phenomenon of mobility of the patterns of bands on the surface of 3D diffusely reflecting objects. Its use in measuring deformations encounters difficulties due to the poor definiteness of the obtained equations of spatial measurements. Therefore, at present, double exposure of speckle holograms is widely used, one before applying a load or at some stage of loading an object, the other after applying an additional load. After photo processing of such a hologram, while viewing it on the reconstructed image, it is possible to study the changes in the object, its stress-strain state. The stress  $\sigma$  and deformation of the surface  $\varepsilon$  from the interferogram when filtering the double exposure speckle holograms are determined as follows [43]:

$$\sigma = E\varepsilon, \quad (2)$$

$$\varepsilon = \frac{U_\lambda}{A}, \quad (3)$$

where,  $E$  is the modulus of elasticity,  $U_\lambda$  is the price of bands on the speckle interferogram,  $A$  is the band pitch.

$$U_{\lambda} = \frac{\lambda}{\sin \alpha}, \tag{4}$$

$$\sin \alpha = x f, \tag{5}$$

where:  $\lambda$  is the wavelength of the used illumination of the speckle hologram,  $f$  is the focal length of the lens that performs the Fourier transform during filtering.

$$\sin \alpha = \text{tg } a \tag{6}$$

at small angles of filtration of spatial frequencies, where  $a$  is the diffraction filtration angle.

Thus, mathematically, a speckle-interferometric image is obtained in a comparative analysis of the matrices of two images, where the first matrix characterises the "undeformed" image, the second - the deformed one. The matrices themselves consist of  $M \times N$  cells with data on the image intensity  $L$ . Since the images are presented in grayscale (Grayscale model), we have  $L$  values with non-negative numbers in the range 0-255. Here:

$$M = [kx] + 1 \tag{7}$$

$$N = [ky] + 1 \tag{8}$$

$$k = \Delta_{ph} / \Delta_r, \tag{9}$$

where  $k$  is the sampling rate, and  $\Delta_{ph}$ ,  $\Delta_r$  is the fraction of the size of the elements in a digital photograph and its meaning in reality, respectively. Subtracting the resulting matrices, we obtain a matrix with  $M \times N$  cells with data  $\Delta L = f(x, y)$ . Here  $x$  and  $y$  are spatial coordinates (on a plane). It is this one that determines the regularities of changes in surface deformations by parameter  $L$ .

Image processing is carried out using the graphic application of the Image Processing Toolbox (IPT) package of the MatLab programme [44-50]. The bands are characterised by positive or negative  $\Delta L$  values. Light bands are characterised by positive  $\Delta L$  values. Dark bands correspond to negative  $\Delta L$  values in the matrix  $\Delta L = f(x, y)$ . Using the image or contour Matlab functions, graphs  $\Delta L = f(x, y)$  are built. In these bands, a change in the sign of the voltage occurs, which is estimated by a change in the value of  $\Delta L$ . Figure 1 demonstrates a speckle-interferometric image and its display in Matlab (image functions, contour). The obtained results suggest that the geometric dimensions of the bands are practically equal [51-57].

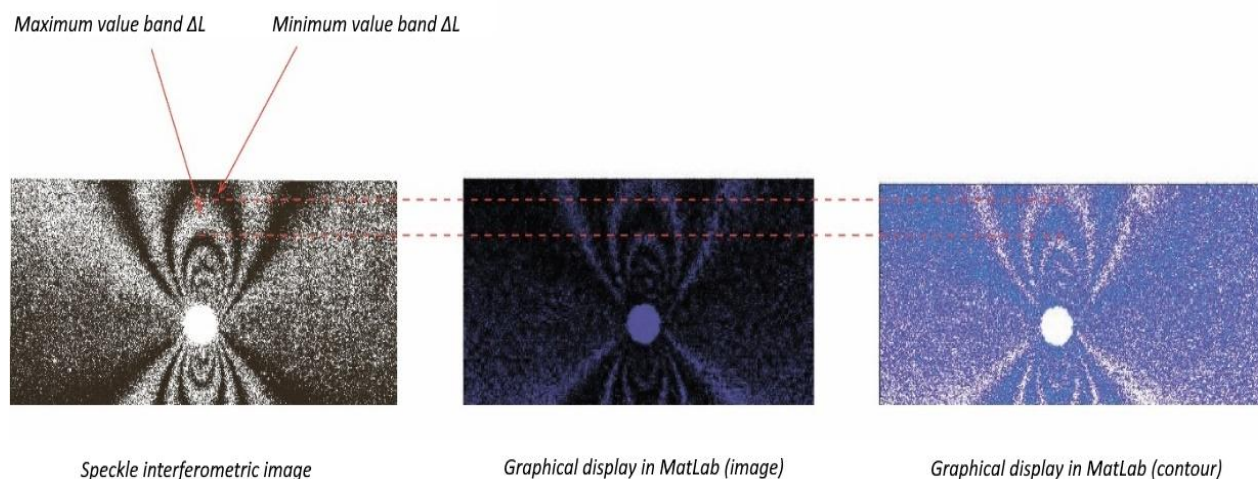


Figure 1. Comparative analysis of speckle-interferometric image and graphical display in MatLab

Depending on the conditions of material deformation, the dynamics of changes  $\Delta L$  in the band can have one or several peaks, or a wave character (Figure 2, a)

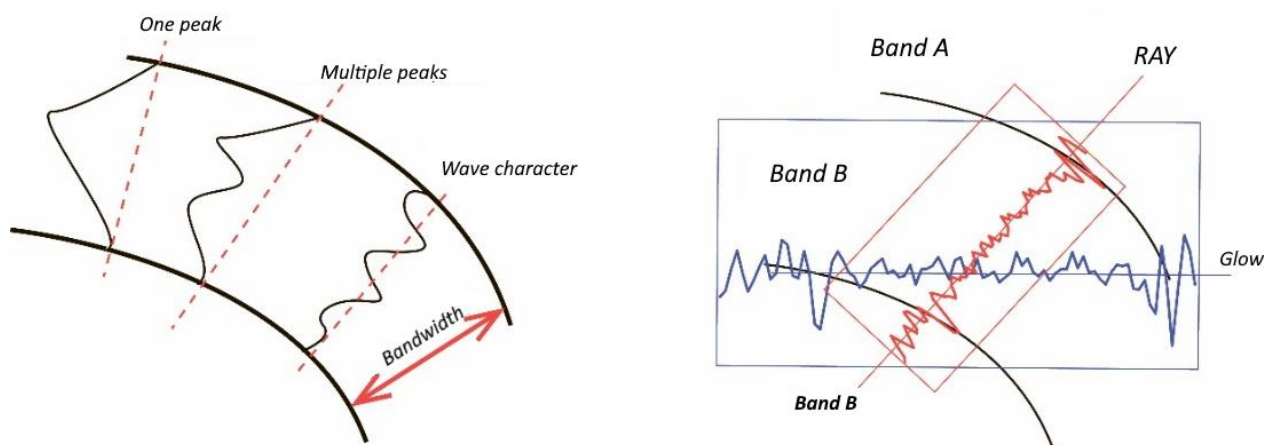


Figure 2. Variants of the dynamics of changes  $\Delta L$  in the section of the band: a) - depending on the conditions of deformation of the material; b) - depending on the shape of the band

For the case of one vertex [58-64], it is advisable to compare the dynamics of changes in different sections of the band according to the value of  $\Delta L$  at the vertex, for variants with several vertices and of a wave nature – according to the average value in the section of the band  $\overline{\Delta L}$  and the rms spread of  $S_{\Delta L}$ .

$$\overline{\Delta L} = \frac{\sum_{i=1}^k \Delta L_i}{k}, \quad (10)$$

$$S_{\Delta L} = \frac{\sqrt{\sum_{i=1}^k (\Delta L_i - \overline{\Delta L})^2}}{k-1}. \quad (11)$$

Here  $k$  is the number of measurements  $\Delta L$  in a given section of the band.

Figure 2b demonstrates a scheme for analysing the change in  $\Delta L$  depending on the shape of the band. It is advisable to analyse the change in  $\Delta L$  depending on the curvature of the band along the ray (radial method) or in longitudinal (or cross) sections. The use of the ray method is necessary when the curvature of the band boundary is large, i.e., in the variant with an approximate position of the beam normal to the band boundary. In the second case – in versions with low curvature and complexity of the beam in the "combined" versions [65-68].

### 3. Results and Discussion

Shown in Figure 3, b is a speckle-interferometric image of a plate made of D-16T material 6 mm thick with a hole 6 mm in diameter at the stage of loading with a differential load of 1.7 tf. [69-76]. Analysis of the law of variation of  $\Delta L$ , the width of the band  $H$  in the given cross-sections along band 1 from 20 to 180 mm with a step of 40 mm are presented in Figures 3a, 3b. The dynamics of the change in the width of the  $H$  band from the minimum value in section 20 and a gradual increase to section 180 is clearly visible. In this case, the shape of the change  $\Delta L$  in the sequence of sections is deformed from a single-vertex view to a two-vertex and three-vertex views. And the value of  $\Delta L_{\max} - \Delta L_{\min}$  (the difference in bands 1 and 2) has a slight tendency to fall. There is a certain "defect" in the region of sections 140-180, which makes its own corrections [77-84].

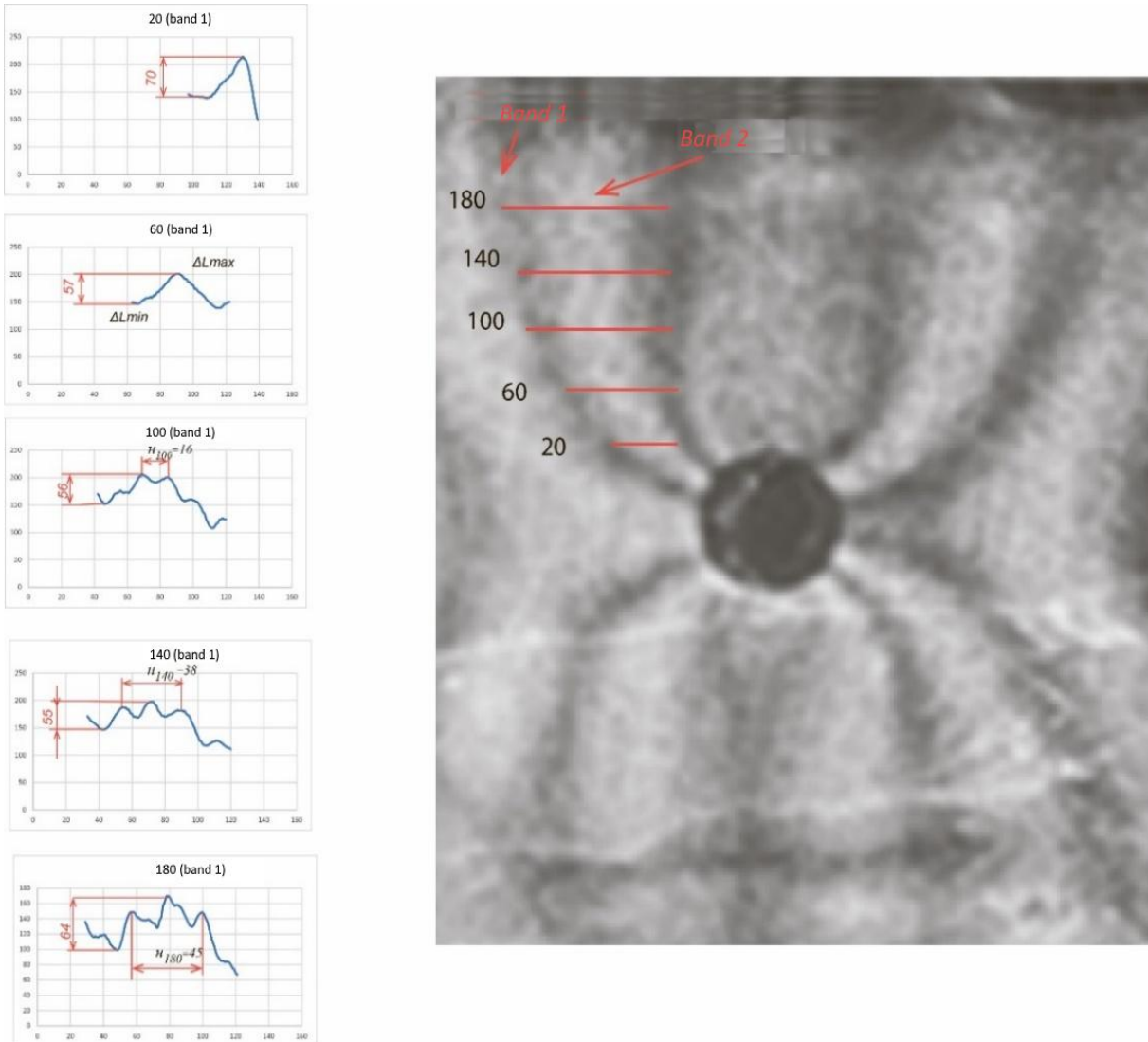


Figure 3. Dynamics of changing  $\Delta L$  depending on the longitudinal section: a) – analysis of the law of changing; b) – speckle-interferometric image of the plate

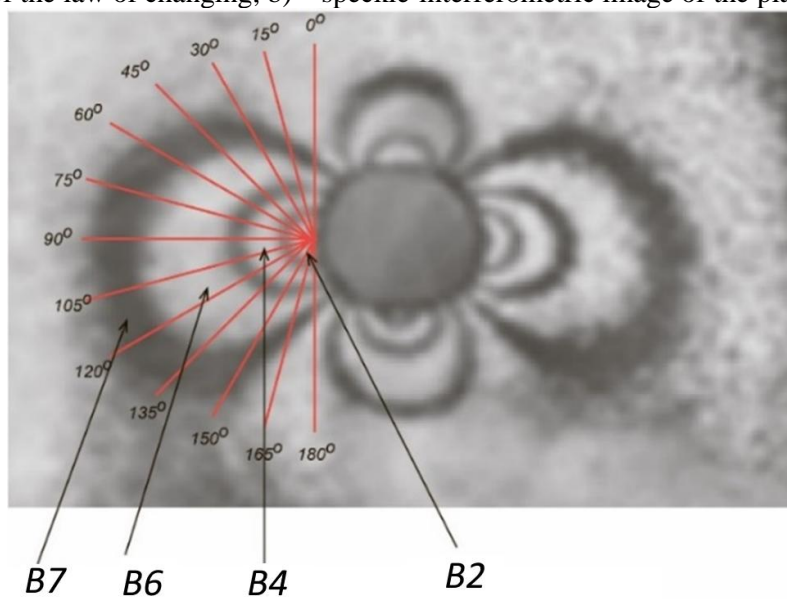
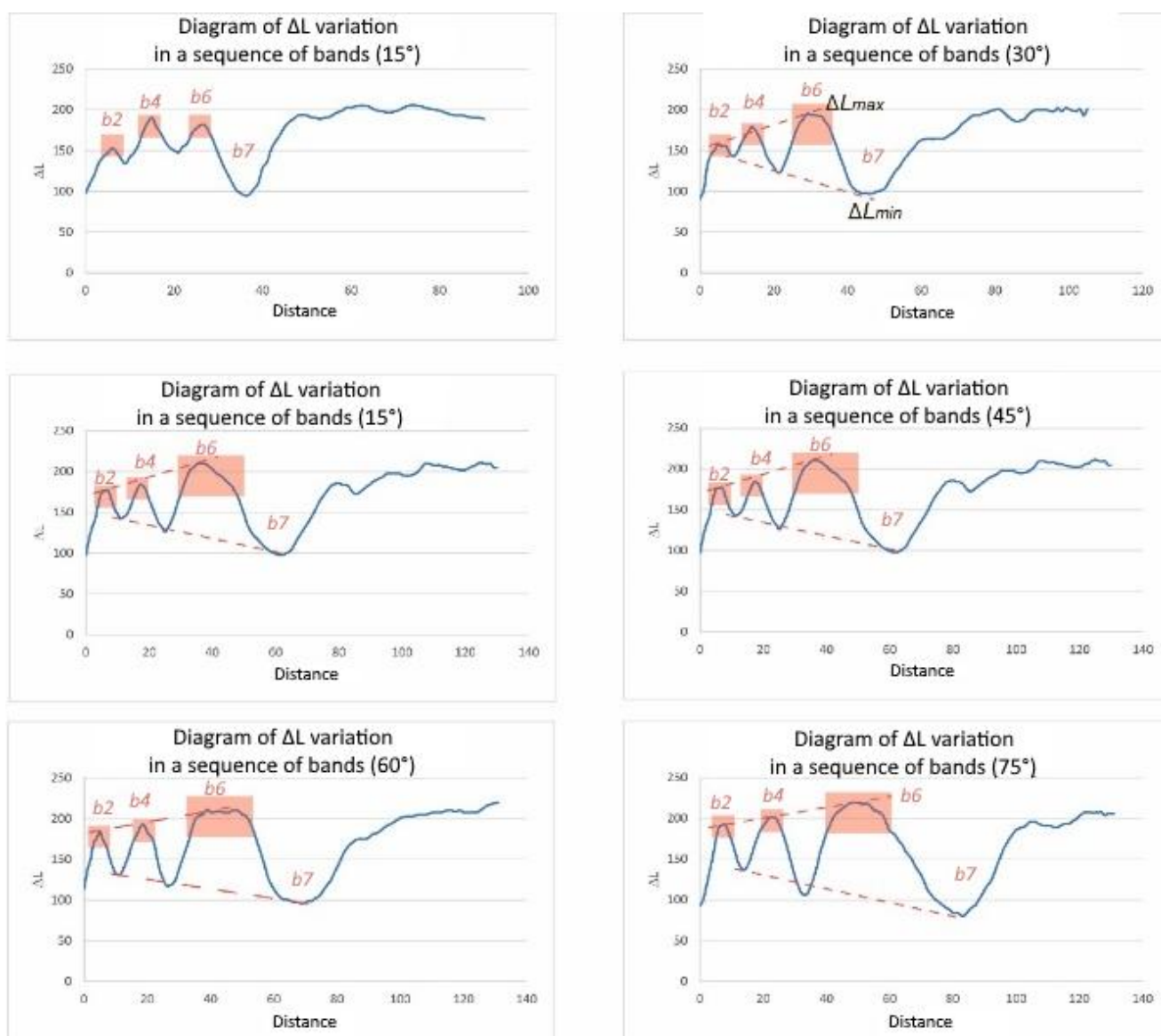


Figure 4. Scheme for measuring the intensity of the image in bands using the ray method (where B7, B6, B4, B2 are the designation of the band number)

In the next speckle image [85-90] (Figure 4), we have almost circular bands. For this variant of the study, it is advisable to analyse the change in the intensity of the image using the ray method. Here, the rays are located at different angles. In this case, for the cases of  $0^\circ$ ,  $90^\circ$ , the ray method is transformed into a measurement method along the longitudinal section.

Figure 5 demonstrates the sequence of changes in the diagrams in the sequence of rays in the range of  $15^\circ$ - $165^\circ$ . A forced “increasing” process is clearly seen, based on a harmonious change in the amplitude  $\Delta L_{max}$ - $\Delta L_{min}$  and the value of the harmonic width  $l$ . Here, the energy from the drilling mechanism in the material is converted into mechanical three-amplitude plastic deformation. In band 7, almost complete attenuation occurs. It should be noted that the cross section of  $90^\circ$  and after it ( $105^\circ$ - $165^\circ$ ), the amplitude vibration differs in shape from the oscillatory processes in the sections of  $15^\circ$ - $75^\circ$ . The values of  $\Delta L_{max}$  in the bands P2, P4, P6 are practically the same, and in the case of cross sections  $15^\circ$ - $75^\circ$  it has a growth tendency [91-93].



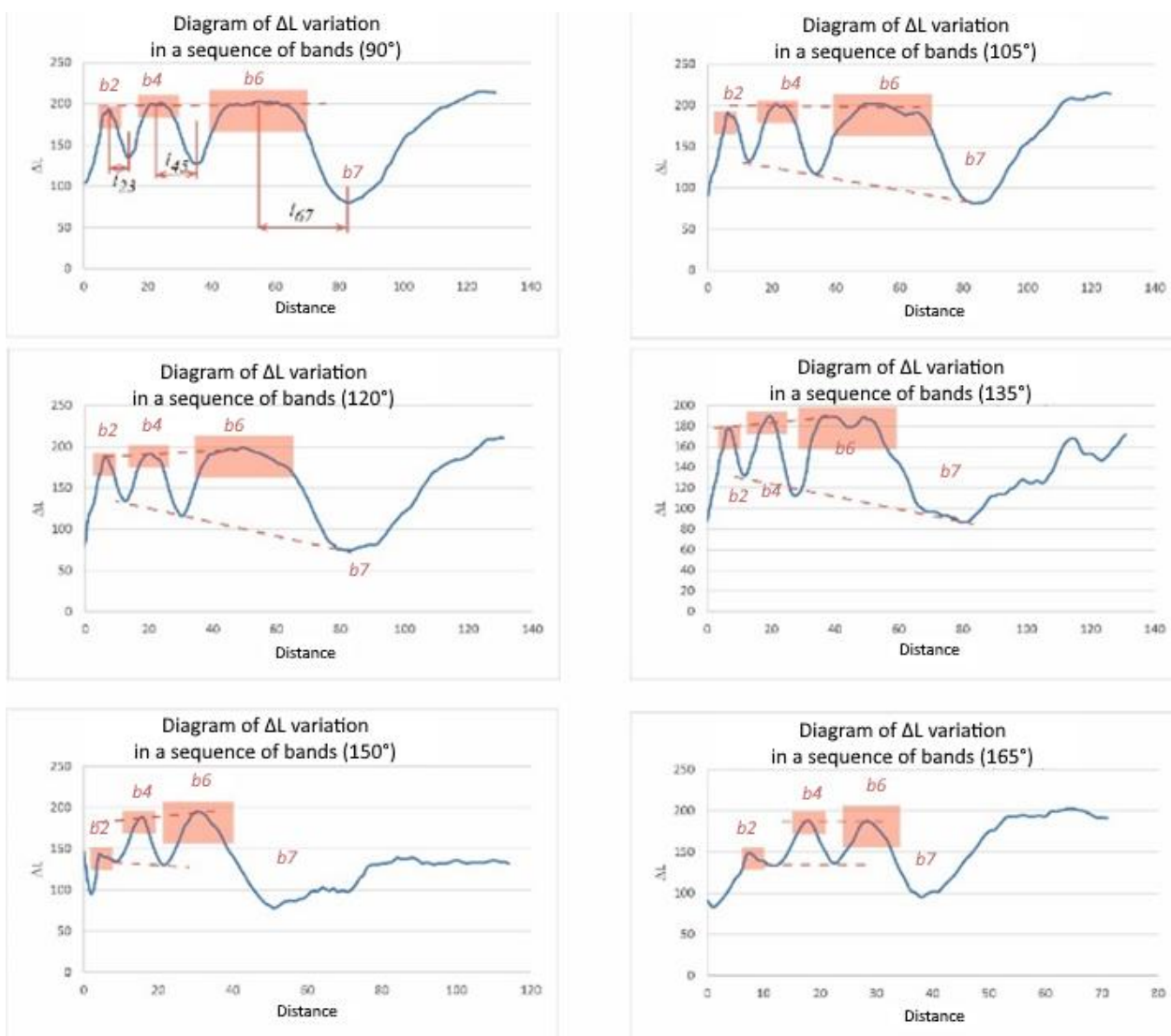
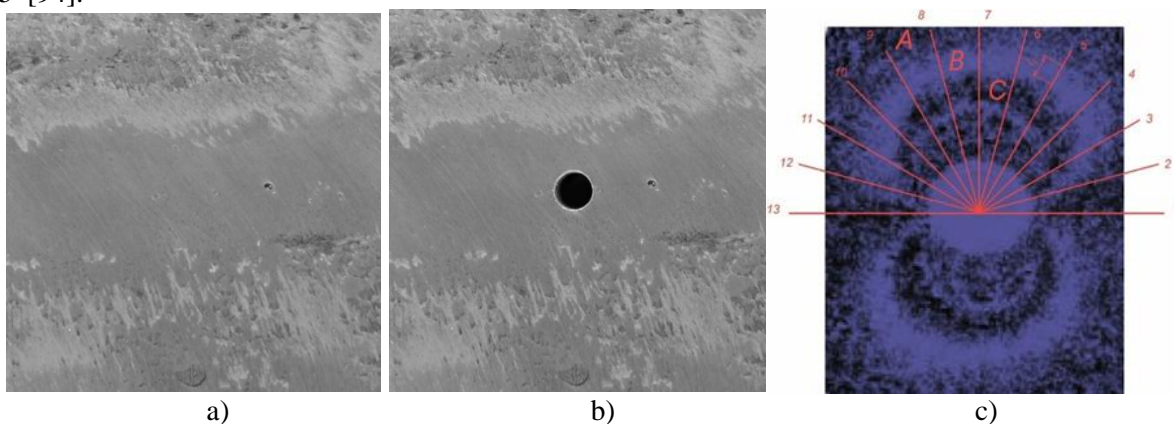


Figure 5. Diagrams of changing  $\Delta L$  in bands in the range of  $15^\circ$ - $165^\circ$ .

A 1.9 mm hole was drilled in the aluminium alloy plate (Figure 6, a). Using the apparatus of the graphic application of the Image Processing Toolbox (IPT) package of the Matlab programme, the data array  $\Delta L$ , proceeding from the matrices before and after drilling the plate, was obtained. The law of variation in the  $B$  band was investigated (Figure 6, b, c), where  $L_{hi}$ ,  $L_{oi}$  is the intensity of the image in a given  $i$ -th cell in a plate with and without a hole was investigated. Next, the upper part of the image is divided into 13 rays at an angle of  $15^\circ$  [94].



a) b) c)  
 Figure 6. Plate before drilling (a), plates with a hole (b), the layout of the rays on the display in MatLab (c)

On the band  $B$  on the  $j$ -th ray, the segment  $l_j$  was chosen (Figure 4), which characterises its width. Further the diagrams  $L_{hj}$ ,  $L_{0j}$ ,  $\Delta L_j = f(x,y)$  and estimates of their average values depending on the direction were built on it (Figure 7). The data obtained are displayed in Figure 8, a.

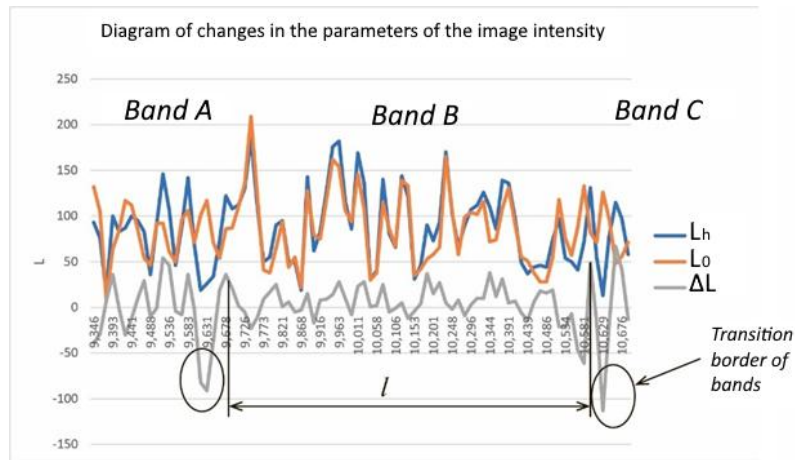


Figure 7. Dynamics of changes in intensity parameters in the cross section of the band

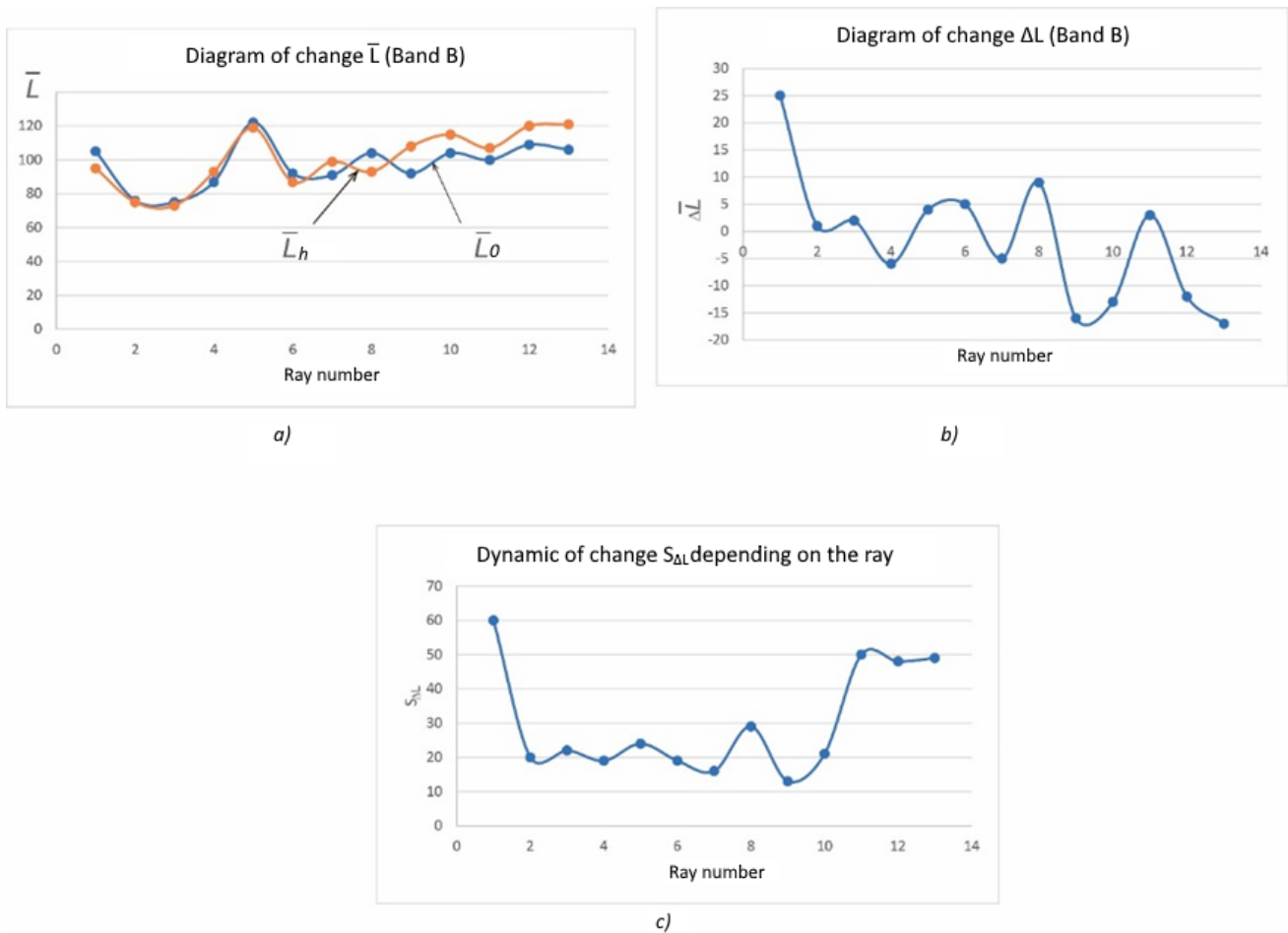


Figure 8. Dynamics of change of holes  $\bar{L}_{oms}$ ,  $\bar{L}_o$  (a),  $\Delta \bar{L}$  (b) and  $S_{\Delta L}$  (c)

It can be seen that the change of  $\bar{L}_h$ ,  $\bar{L}_o$ ,  $\Delta \bar{L}$  have a wave character. Beam 7 (angle  $90^\circ$ ) is a “theoretical” inflection point, where  $\bar{L}_h$ ,  $\bar{L}_o$ , with some difference in values stabilise and grow from beam 7 to beam 13



(Figure 8, b). This is reflected in the dynamics of change  $\Delta\bar{L}$ . On rays 1 and 13, we have values opposite in sign ( $\Delta\bar{L}$  are, respectively, 1.72 and  $-2.97$ ). Their difference is more than 2.7 times. Thus, we can assume that at these poles there is a stress state of different sign. On beams 2-8, the value of  $\Delta\bar{L}$  has a downward trend from beam 1 to beam 13. In this case, the assessment  $\Delta\bar{L}$ ,  $S_{\Delta L}$  on rays 1, 13 was carried out at a distance of one diameter from the beginning of the hole (Figure 8, c), since these rays are at the beginning of the nucleation of the  $B$  band. It should be noted that on beams 1 and 13 there is a maximum spread  $S_{\Delta L}$ . It can be considered that the points on the hole 1 and 2 (Figure 8, c) (rays 1, 13) are, as it were, the generators of wave processes in the bands.

Based on Figure 9, it can be seen that at points 1 and 2 there is a difference in the values of  $L$ , which is characterised by the value  $\Delta L_{1-2}$ . At the same time, for beam 13 we have at the beginning a decreasing tendency of  $L$  change, for beam 1 it is increasing (antiphase movement of deformation). In the longitudinal section, the amplitude fluctuation of the image intensity with the  $\Delta l_x$  wave is clearly visible. Inside this wave, there are "internal" oscillations  $\Delta li$ . In this case,  $\Delta l_x$ ,  $\Delta li$  change both in the direction of increasing (stretching) and in the direction of decreasing (compression). The  $\Delta l_x$  value and the  $L_{max}-L_{min}$  amplitude in this wave determine the "force" of plastic deformation, and therefore contribute to the formation of the "geometry" of the fringe and the total number of interference fringes [95; 96].

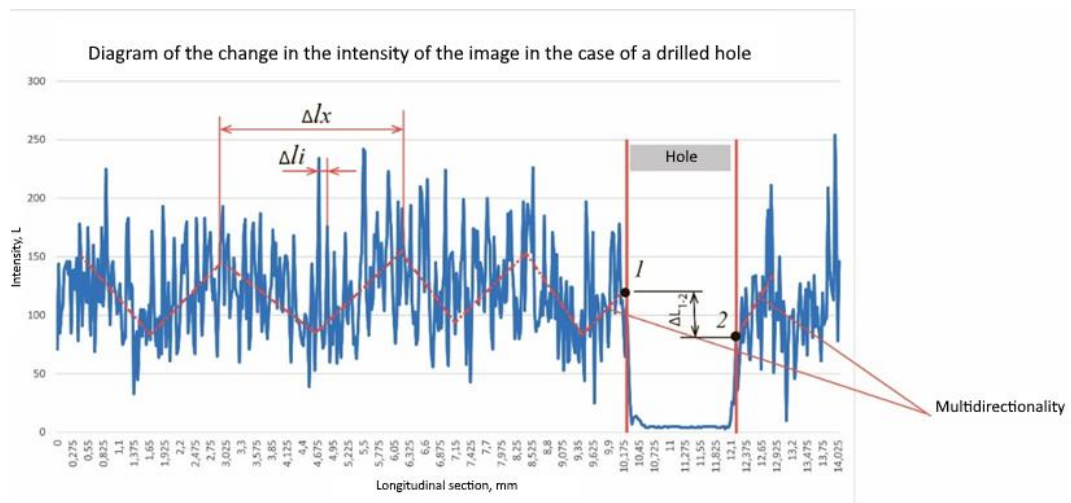


Figure 9. Dynamics of changes in  $L$  on beams 1.13 on a sample with a drilled hole

#### 4. Conclusion

In this study, the authors developed a method for assessing the dynamics of changes in the image intensity in the investigated band (bands) of the speckle-interferometric image. It was demonstrated that, depending on the position of the beam on the hole (the point of the onset of deformation), a wave process of changing the image intensity occurs. The criterion for evaluating the comparison of the dynamics of change in the image intensity in the cross sections of the band(s) can be the maximum value at the vertex (one-vertex case) or the average value of the change in intensity (with its standard deviation). The section in a given band, depending on its curvature, must be determined by the ray method or by transverse or longitudinal sections.

It was proved that the applied method does not depend on "external" factors: material structure, defectiveness, etc. It allows drawing quantitative and qualitative comparative conclusions for different variants of research objects. It was proved that the applied method allows estimating the boundaries of the bands with a given probability, and hence their area, which is critical in comparative studies of different speckle-interferometric images. The presented algorithm allows evaluating the dynamics of the change in the process in the given bands, which in turn enables the evaluation of the uniformity of plastic deformation in the sample.

#### Acknowledgments

The study was carried out with the financial support of the state project of the Ministry of Education and Science on the subject "Theoretical and experimental research in production and processing of advanced metal and composite materials based on aluminium and titanium alloys" FSFF-2020-0016.

---

**References**

- [1] T. S. Suprapedi, “Spatio-Temporal Observation of Plastic Deformation and Fracture by Laser Speckle Interferometry,” *Physical mesomechanics*, no. 1, pp. 55–60, 1998.
- [2] V. S. Pisarev, S. I. Eleonsky and A. I. Chernov, “Residual Stress Determination in Orthotropic Composites by Displacement Measurements Near Through Hole,” *Experimental Mechanics*, no. 55, pp. 1225–1238, 2015.
- [3] V. S. Pisarev, Y. G. Matvienko, S. I. Eleonsky and I. N. Odintsev, “Combining the Crack Compliance Method and Speckle Interferometry Data for Determination of Stress Intensity Factors and T-Stresses,” *Engineering Fracture Mechanics*, no. 179, pp. 348–374, 2017.
- [4] V. Pisarev, I. Odintsev, S. Eleonsky and A. Apalkov, “Residual Stress Determination by Optical Interferometric Measurements of Hole Diameter Increments,” *Optics and Lasers in Engineering*, no. 110, pp. 437–456, 2018.
- [5] S. G. Lekhnitsky, *Theory of Elasticity of an Anisotropic Elastic Body*, Moscow: Nauka, 1977.
- [6] P. P. Parlevliet, H. E. N. Bersee and A. Beukers, “Residual Stresses in Thermoplastic Composites – A Study of the Literature – Part I: Formation of Residual Stresses,” *Composites Part A: Applied Science and Manufacturing*, vol. 370, no. 11, pp. 1847–1857, 2006.
- [7] D. Stavrov and N. E. N. Bersee, “Resistance Welding of Thermoplastic Composites – An Overview,” *Composites Part A: Applied Science and Manufacturing*, vol. 36, no. 1, pp. 39–54, 2005.
- [8] I. V. Volkov, “Using the Speckle Holography Method in Experimental Mechanics,” *Measuring technology*, no. 2, pp. 42–46, 2017.
- [9] V. I. Volkov, M. H. Nyan, H. O. Wai and M. L. Tun, “Determination of Physicomechanical Characteristics of Materials in the Study of Concentration Stresses on Samples with Holes,” *Trudy MIPT*, vol. 10, no. 1, pp. 68–74, 2018.
- [10] M. H. Nyan, I. B. Volkov, M. L. Tun and H. O. Wai, “Study of Stress Concentration and Stress-Strain State in Full-Scale Samples of Aircraft Structures,” *Trudy MIPT*, vol. 11, no. 3, pp. 146–154, 2019.
- [11] E. B. Alexandrov and A. M. Bonch-Bruevich, “Investigation of Surface Deformations of Bodies Using Holographic Technology,” *Journal of Engineering Physics*, no. 37, pp. 360–369, 1967.
- [12] A. V. Babaytsev, E. L. Kuznetsova, L. N. Rabinskiy and O. V. Tushavina, “Investigation of Permanent Strains in Nanomodified Composites after Moulding at Elevated Temperatures,” *Periodico Tche Quimica*, vol. 17, no. 34, pp. 1055–1065, 2020.
- [13] V. V. Bodryshev, “Analysis of the Structure of the Material According to the Criterion — The Intensity of the Image of the Photograph,” *Journal “Technology of materials”*, no. 11, pp. 8–12, 2017.
- [14] V. V. Bodryshev, A. V. Babaytsev and L. N. Rabinskiy, “Investigation of Processes of Deformation of Plastic Materials with the Help of Digital Image Processing,” *Periódico Tchê Química*, vol. 16, no. 33, pp. 865–876, 2019.
- [15] N. A. Bulychev, V. V. Bodryshev and L. N. Rabinskiy, “Analysis of Geometric Characteristics of Two-Phase Polymer-Solvent Systems During the Separation of Solutions According to the Intensity of the Image of Micrographs,” *Periodico Tche Quimica*, vol. 16, no. 32, pp. 551–559, 2019.
- [16] N. A. Bulychev and L. N. Rabinskiy, “Ceramic Nanostructures Obtained by Acoustoplasma Technique,” *Nanoscience and Technology: An International Journal*, vol. 10, no. 3, pp. 279–286, 2019.
- [17] N. A. Bulychev, L. N. Rabinskiy and O. V. Tushavina, “Effect of Intense Mechanical Vibration of Ultrasonic Frequency on Thermal Unstable Low-Temperature Plasma,” *Nanoscience and Technology: An International Journal*, vol. 11, no. 1, pp. 15–21, 2020.
- [18] P. F. Pronina, O. V. Tushavina and E. I. Starovoitov, “Study of the Radiation Situation in Moscow by Investigating Elastoplastic Bodies in a Neutron Flux Taking into Account Thermal Effects,” *Periodico Tche Quimica*, vol. 17, no. 35, pp. 753–764, 2020.

- [19] A. A. Orekhov, Yu. A. Utkin and P. F. Pronina, "Determination of Deformation in Mesh Composite Structure Under the Action of Compressive Loads," *Periodico Tche Quimica*, vol. 17, no. 35, pp. 599–608, 2020.
- [20] E. L. Kuznetsova and A. V. Makarenko, "Mathematic Simulation of Energy-Efficient Power Supply Sources for Mechatronic Modules of Promising Mobile Objects," *Periodico Tche Quimica*, vol. 15, no. 1, pp. 330–338, 2018.
- [21] V. F. Formalev, S. A. Kolesnik and E. L. Kuznetsova, "Analytical Study on Heat Transfer in Anisotropic Space with Thermal Conductivity Tensor Components Depending on Temperature," *Periodico Tche Quimica*, vol. 15, no. 1, pp. 426–432, 2018.
- [22] A. V. Makarenko and E. L. Kuznetsova, "Energy-Efficient Actuator for the Control System of Promising Vehicles," *Russian Engineering Research*, vol. 39, no. 9, pp. 776–779, 2019.
- [23] R. A. Maleev, S. M. Zuev, A. M. Fironov, N. A. Volchkov and A. A. Skvortsov, "The Starting Processes of a Car Engine Using Capacitive Energy Storages," *Periodico Tche Quimica*, vol. 16, no. 33, pp. 877-888, 2019.
- [24] A. A. Skvortsov, D. E. Pshonkin and M. N. Luk'yanov, "Influence of Constant Magnetic Fields on Defect Formation Under Conditions of Heat Shock in Surface Layers of Silicon," *Key Engineering Materials*, no. 771, pp. 124-129, 2018.
- [25] N. M. Fialko, R. O. Navrodska, S. I. Shevchuk and G. O. Gnedash, "The Environmental Reliability of Gas-Fired Boiler Units by App Lying Modern Heat-Recovery Technologies," *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu*, vol. 2020, no. 2, pp. 96-100, 2020.
- [26] V. G. Prokopov, N. M. Fialko, G. P. Sherenkovskaya, V. L. Yurchuk, Yu. S. Borisov, A. P. Murashov and V. N. Korzhik, "Effect of Coating Porosity on the Process of Heat Transfer with Gas-Thermal Deposition," *Powder Metallurgy and Metal Ceramics*, vol. 32, no. 2, pp. 118-121, 1993.
- [27] N. Khripach, L. Lezhnev, A. Tatarnikov, R. Stukolkin and A. Skvortsov, "Turbo-Generators in Energy Recovery Systems," *International Journal of Mechanical Engineering and Technology*, vol. 9, no. 6, pp. 1009-1018, 2018.
- [28] R. V. Dinzhos, N. M. Fialko and E. A. Lysenkov, "Analysis of the Thermal Conductivity of Polymer Nanocomposites Filled with Carbonnanotubes and Carbon Black," *Journal of Nano- and Electronic Physics*, vol. 6, no. 1, article number 01015, 2014.
- [29] D. V. Dinzhos, E. A. Lysenkov and N. M. Fialko, "Influence of Fabrication Method and Type of the Filler on the Thermal Properties of Nanocomposites Based on Polypropylene," *Voprosy Khimii i Khimicheskoi Tekhnologii*, vol. 2015, no. 5, pp. 56-62, 2015.
- [30] N. Fialko, R. Navrodska, M. Ulewicz, G. Gnedash, S. Alioshko and S. Shevcuk, "Environmental Aspects of Heat Recovery Systems of Boiler Plants," *E3S Web of Conferences*, no. 100, article number 00015, 2019.
- [31] I. A. Kapitonov, "Legal Support for Integration of Renewable Energy Sources in the Energy Law of the Countries from the International Legal Position," *Kuwait Journal of Science*, vol. 46, no. 1, pp. 68-75, 2019.
- [32] M. M. Lazarenko, K. I. Hnatiuk, S. A. Alekseev, K. S. Yablochkova, R. V. Dinzhos, F. Ublekov, M. V. Lazarenko, D. A. Andrusenko and A. N. Alekseev, "Low-Temperature Dielectric Relaxation in the System Silica Gel – Undecylenic Acid," in *Proceedings of the 2020 IEEE 10th International Conference on "Nanomaterials: Applications and Properties", NAP 2020*, article number 9309579, Sumy, Ukraine, pp. 9-13 November, 2020.
- [33] A. Zvorykin, N. Fialko, S. Julii, S. Aleshko, N. Meranova, M. Hanzha, I. Bashkir, S. Stryzheus, A. Voitenko and I. Pioro, "CFD Study on Specifics of Flow and Heat Transfer in Vertical Bare Tubes Cooled with Water at Supercritical Pressures," *International Conference on Nuclear Engineering, Proceedings, ICONE*, no. 9, pp. 1-13, 2017.

- [34] I. A. Kapitonov, T. G. Filosofova and V. G. Korolev, "Development of Digital Economy in the Energy Industry-Specific Modernization," *International Journal of Energy Economics and Policy*, vol. 9, no. 4, pp. 273-282, 2019.
- [35] N. M. Fialko, V. G. Prokopov, N. O. Meranova, Yu. S. Borisov, V. N. Korzhik and G. P. Sherenkovskaya, "Single Particle-Substrate Thermal Interaction During Gas-Thermal Coatings Fabrication," *Fizika i Khimiya Obrabotki Materialov*, no. 1, pp. 70-78, 1994.
- [36] A. Zvorykin, S. Aleshko, N. Fialko, N. Maison, N. Meranova, A. Voitenko and I. Piore, "Computer Simulation of Flow and Heat Transfer in Bare Tubes at Supercritical Parameters," *International Conference on Nuclear Engineering, Proceedings, ICONE*, no. 5, pp. 1-12, 2016.
- [37] I. A. Kapitonov, "Low-Carbon Economy as the Main Factor of Sustainable Development of Energy Security," *Industrial Engineering and Management Systems*, vol. 19, no. 1, pp. 3-13, 2020.
- [38] R. Dinzhos, E. Lysenkov and N. Fialko, "Simulation of Thermal Conductivity of Polymer Composites Based on Poly (Methyl Methacrylate) with Different Types of Fillers," *Eastern-European Journal of Enterprise Technologies*, vol. 6, no. 11, pp. 21-24, 2015.
- [39] D. G. Blinov, V. G. Prokopov, Yu. V. Sherenkovskii, N. M. Fialko, and V. L. Yurchuk, "Effective Method for Construction of Low-Dimensional Models for Heat Transfer Process," *International Journal of Heat and Mass Transfer*, vol. 47, no. 26, pp. 5823-5828, 2004.
- [40] I. A. Kapitonov, "Development of Low-Carbon Economy as the Base of Sustainable Improvement of Energy Security," *Environment, Development and Sustainability*, vol. 23, no. 3, pp. 3077-3096, 2021.
- [41] N. M. Fialko, V. G. Prokopov, N. O. Meranova, Yu. S. Borisov, V. N. Korzhik and G. P. Sherenkovskaya, "Heat Transport Processes in Coating-Substrate Systems Under Gas-Thermal Deposition," *Fizika i Khimiya Obrabotki Materialov*, no. 2, pp. 68-75, 1994.
- [42] Y. S. Oryngozhin, G. Z. Moldabayeva and I. B. Igembayev, "Innovative Method of High-Viscosity Oil Production", *12th International Multidisciplinary Scientific GeoConference and EXPO - Modern Management of Mine Producing, Geology and Environmental Protection, SGEM 2012*, no. 2, pp. 463-470, 2012.
- [43] I. A. Kapitonov, "Transformation of Social Environment in the Application of Alternative Energy Sources," *Environment, Development and Sustainability*, vol. 22, no. 8, pp. 7683-7700, 2020.
- [44] N. I. Dorogov, I. A. Kapitonov and N. T. Batyrova, "The Role of National Plans in Developing the Competitiveness of the State Economy," *Entrepreneurship and Sustainability Issues*, vol. 8, no. 1, pp. 672-686, 2020.
- [45] E. Ginters, A. Aizstrauts and R.M.A. Chinae, "Sociotechnical Aspects of Policy Simulation," in *Handbook of Research on Advanced ICT Integration for Governance and Policy Modeling*, Hershey: IGI Global, 2014.
- [46] G. P. Metaksa, G. Z. Moldabayeva and Z. N. Alisheva, "Mechanism of Structure Formation in Fluid-Bearing Minerals," *Mining Informational and Analytical Bulletin*, vol. 2019, no. 2, pp. 78-84, 2019.
- [47] M. N. Rudenko, "Entrepreneurship Development Trends in Perm and Sverdlovsk Region," *Journal of Advanced Research in Law and Economics*, vol. 11, no. 3, pp. 993-1008, 2020.
- [48] G. M. Karasayev, K. A. Yensenov, K. M. Aldabergenov, B. S. Zhumagulov and T. M. Aminov, "From the History of International Economic, Industrial and Political Relations Between Kazakhstan and Russian Federation (1991-1998)," *Journal of Advanced Research in Law and Economics*, vol. 10, no. 5, pp. 1434-1437, 2019.
- [49] M. Y. Kharlamov, I. V. Krivtsun, V. N. Korzhyk, Y. V. Ryabovolyk and O. I. Demyanov, "Simulation of Motion, Heating, and Breakup of Molten Metal Droplets in the Plasma Jet at Plasma-Arc Spraying," *Journal of Thermal Spray Technology*, vol. 24, no. 4, pp. 659-670, 2015.
- [50] Yu. S. Borisov, V. E. Olikier, E. A. Astakhov, V. N. Korzhik and Yu. A. Kunitskii, "Structure and Properties of Gas-Thermal Coatings of Fe-B-C and Fe-Ti-B-C Alloys," *Soviet Powder Metallurgy and Metal Ceramics*, vol. 26, no. 4, pp. 313-318, 1987.

- [51] R. Dinzhos, N. Fialko, V. Prokopov, Y. Sherenkovskiy, N. Meranova, N. Koseva, V. Korzhik, O. Parkhomenko and N. Zhuravskaya, "Identifying the Influence of the Polymer Matrix Type on the Structure Formation of Microcomposites When They Are Filled with Copper Particles," *Eastern-European Journal of Enterprise Technologies*, vol. 5, no. 6-107, pp. 49-57, 2020.
- [52] O. V. Chernets, V. M. Korzhyk, G. S. Marynsky, S. V. Petrov and V. A. Zhovtyansky, "Electric Arc Steam Plasma Conversion of Medicine Waste and Carbon Containing Materials," *GD 2008 - 17th International Conference on Gas Discharges and Their Applications*, no. 1, pp. 465-468, 2008.
- [53] G. M. Hryhorenko, L. I. Adeeva, A. Y. Tunik, M. V. Karpets, V. N. Korzhyk, M. V. Kindrachuk and O. V. Tisov, "Formation of Microstructure of Plasma-Arc Coatings Obtained Using Powder Wires with Steel Skin and B4C + (Cr, Fe)7C3 + Al Filler," *Metallofizika i Noveishie Tekhnologii*, vol. 42, no. 9, pp. 1265-1282, 2020.
- [54] G. Z. Moldabayeva, G. P. Metaxa and Z. N. Alisheva, "Theoretical Bases for the Implementation of the Processes to Reduce Viscosity in the Conditions of Natural Reservation". *News of the National Academy of Sciences of the Republic of Kazakhstan, Series of Geology and Technical Sciences*, vol. 5, no. 437, pp. 138-143, 2019.
- [55] B. Kovačič, R. Kamnik and A. Bieliatynskiy, "The Different Methods of Displacement Monitoring at Loading Tests of Bridges or Different Structures," *MATEC Web of Conferences*, no. 53, 01048, 2016.
- [56] G. Z. Moldabayeva, G. P. Metaxa and Z. N. Alisheva, "Scientific-Technical Basics of Viscosity Reduction of the Kazakhstani Oils, Which Provide a Significant Increase of Oil Reservoirs," *News of the National Academy of Sciences of the Republic of Kazakhstan, Series of Geology and Technical Sciences*, vol. 3, no. 430, pp. 186-194, 2018.
- [57] V. N. Korzhyk, L. D. Kulak, V. E. Shevchenko, V. V. Kvasnitskiy, N. N. Kuzmenko, X. Liu, Y. X. Cai, L. Wang, H. W. Xie and L. M. Zou, "New Equipment for Production of Super Hard Spherical Tungsten Carbide and Other High-Melting Compounds Using the Method of Plasma Atomization of Rotating Billet", *Materials Science Forum*, no. 898, pp. 1485-1497, 2017.
- [58] I. P. Gulyaev, A. V. Dolmatov, M. Y. Kharlamov, P. Y. Gulyaev, V. I. Jordan, I. V. Krivtsun, V. M. Korzhyk and O. I. Demyanov, "Arc-Plasma Wire Spraying: An Optical Study of Process Phenomenology," *Journal of Thermal Spray Technology*, vol. 24, no. 8, pp. 1566-1573, 2015.
- [59] A. Aizstrauts, E. Ginters, M. Baltruks and M. Gusev, "Architecture for Distributed Simulation Environment," *Procedia Computer Science*, no. 43C, pp. 18-25, 2015.
- [60] V. V. Shlychkov, I. K. Kiyamov, A. S. Khasanova, S. M. Kulish and D. R. Nestulaeva, "Hands-On Management: Theoretical and Methodological Approaches and Russian Practice of State and Municipal Management," *European Research Studies Journal*, vol. 20, no. 2, pp. 200-223, 2017.
- [61] G. Moldabayeva, R. Suleimenova, A. Karimova, N. Akhmetov and L. Mardanova, "Experimental Support of Field Trial on the Polymer Flooding Technology Substantiation in the Oil Field of Western Kazakhstan," *Periodico Tche Quimica*, vol. 17, no. 35, pp. 663-677, 2020.
- [62] S. Z. Mirzaev and U. Kaatze, "Dynamic Scaling in the Ultrasonic Attenuation Spectra of Critical Binary Mixtures," *Chemical Physics Letters*, vol. 328, no. 3, pp. 277-282, 2000.
- [63] A. Bieliatynskiy, E. Krayushkina and A. Skrypchenko, "Modern Technologies and Materials for Cement Concrete Pavement's Repair," *Procedia Engineering*, no. 134, pp. 344-347, 2016.
- [64] K. Krayushkina, O. Prentkovskis, A. Bieliatynskiy, J. Gigineishvili, A. Skrypchenko, A. Laurinavicius, K. Gopalakrishnan and J. Tretjakovas, "Perspectives on Using Basalt Fiber Filaments in the Construction and Rehabilitation of Highway Pavements and Airport Runways," *Baltic Journal of Road and Bridge Engineering*, vol. 11, no. 1, pp. 77-83, 2016.
- [65] A. Aizstrauts, E. Ginters, I. Lauberte and M.A.P. Eroles, "Multi-Level Architecture on Web Services-Based Policy Domain Use Cases Simulator," *Lecture Notes in Business Information Processing*, no. 153, pp. 130-145, 2013.
- [66] M. Yu. Kharlamov, I. V. Krivtsun and V. N. Korzhyk, "Dynamic Model of the Wire Dispersion Process in Plasma-Arc Spraying," *Journal of Thermal Spray Technology*, vol. 23, no. 3, pp. 420-430, 2014.

- [67] A. Onishchenko, L. Stolyarova and A. Bieliatynskiy, "Evaluation of the Durability of Asphalt Concrete on Polymer Modified Bitumen," *E3S Web of Conferences*, no. 157, 06005, 2020.
- [68] G.M. Grigorenko, L.I. Adeeva, A.Y. Tunik, V.N. Korzhik and M.V. Karpets, "Plasma Arc Coatings Produced from Powder-Cored Wires with Steel Sheaths," *Powder Metallurgy and Metal Ceramics*, vol. 59, no. 5-6, pp. 318-329, 2020.
- [69] S. Peleshenko, V. Korzhyk, O. Voitenko, V. Khaskin and V. Tkachuk, "Analysis of the Current State of Additive Welding Technologies for Manufacturing Volume Metallic Products (Review)," *Eastern-European Journal of Enterprise Technologies*, vol. 3, no. 1-87, pp. 42-52, 2017.
- [70] V. Korzhyk, V. Khaskin, O. Voitenko, V. Sydorets and O. Dolianovskaia, "Welding Technology in Additive Manufacturing Processes of 3D Objects," *Materials Science Forum*, no. 906, pp. 121-130, 2017.
- [71] O. Stepanchuk, A. Bieliatynskiy, O. Pylypenko and S. Stepanchuk, "Surveying of Traffic Congestions on Arterial Roads of Kyiv City," *Procedia Engineering*, no. 187, pp. 14-21, 2017.
- [72] O. Stepanchuk, A. Bieliatynskiy, O. Pylypenko and S. Stepanchuk, "Peculiarities of City Street-Road Network Modelling," *Procedia Engineering*, no. 134, pp. 276-283, 2016.
- [73] K.N. Mursalova, B.A. Ainakanova, A.S. Kazkenova, N. Zhalelkanova and O. Ozpence, "Analysis of Problems of Kazakhstan's Economic Integration in the EAEU," *Journal of Advanced Research in Law and Economics*, vol. 11, no. 4, pp. 1218-1232, 2020.
- [74] D. Aizstrauta, A. Celmina, E. Ginters and R. Mazza, "Validation of Integrated Acceptance and Sustainability Assessment Methodology," *Procedia Computer Science*, no. 26, pp. 33-40, 2013.
- [75] D. Aizstrauta and E. Ginters, "Integrated Acceptance and Sustainability Assessment Model Transformations into Executable System Dynamics Model," *Procedia Computer Science*, no. 77, pp. 92-97, 2015.
- [76] R. Baembitov, T. Dokic, M. Kezunovic, Y. Hu and Z. Obradovic, "Fast Extraction and Characterization of Fundamental Frequency Events from a Large PMU Dataset Using Big Data Analytics," *Proceedings of the Annual Hawaii International Conference on System Sciences*, no. 1, pp. 3195-3204, 2021.
- [77] A. Yushchishina, M. Pasichnyk, O. Mitryasova, P. Koszelnik, R. Gruca-Rokosz and M. Kida, "Research of Aggregatic Stability and Bactericidal Activities of Nanosilver Colloidal Solutions," *Rocznik Ochrona Srodowiska*, vol. 22, no. 1, pp. 40-50, 2020.
- [78] S. Oleksandra, K. Krayushkina, T. Khymerik and B. Andrii, "Method of Increasing the Roughness of the Existing Road," *Procedia Engineering*, no. 165, pp.1766-1770, 2016.
- [79] A. Bieliatynskiy, L. Osipa and B. Kornienko, "Water-Saving Processes Control of an Airport," *MATEC Web of Conferences*, no. 239, 05003, 2018.
- [80] D. V. Dinzhos, E. A. Lysenkov and N. M. Fialko, "Influence of Fabrication Method and Type of the Filler on the Thermal Properties of Nanocomposites Based on Polypropylene," *Voprosy Khimii i Khimicheskoi Tekhnologii*, vol. 2015, no. 5, pp. 56-62, 2015.
- [81] A. K. Zhumalina, B. T. Tusupkaliev, M. B. Zharlikasinova, I. S. Kim and K. B. Darzhanova, "Bone Turnover Markers in Children and Adolescents with Environmentally Determined Short Stature, Living in the Oil and Gas Processing Region," *Environmental Science and Pollution Research*, vol. 27, no. 27, pp. 33998-34004, 2020.
- [82] D. G. Blinov, V. G. Prokopov, Yu. V. Sherenkovskii, N. M. Fialko, and V. L. Yurchuk, "Effective Method for Construction of Low-Dimensional Models for Heat Transfer Process," *International Journal of Heat and Mass Transfer*, vol. 47, no. 26, pp. 5823-5828, 2004.
- [83] V. Z. Kutsova, M. A. Kovzel, A. V. Grebeneva and A. S. Myrgorodskaya, "Structure, Phases and Alloying Elements Distribution of Nikorim (High-Temperature Strength Ni-Cr Alloy) in Its Cast Form," *Metallurgical and Mining Industry*, vol. 4, no. 1, pp. 40-44, 2012.

- 
- [84] A. Z. Skorokhod, I. S. Sviridova and V. N. Korzhik, "Structural and Mechanical Properties of Polyethylene Terephthalate Coatings as Affected by Mechanical Pretreatment of Powder in the Course of Preparation," *Mekhanika Kompozitnykh Materialov*, vol. 30, no. 4, pp. 455-463, 1994.
- [85] Y. Borisov, V. Korzhyk and S. Revo, "Electric and Magnetic Properties of Thermal Spray Coatings with an Amorphous Structure," *Proceedings of the International Thermal Spray Conference*, no. 1, pp. 687-691, 1998.
- [86] P. I. Sharikov, A. V. Krasov, A. M. Gelfand and N. A. Kosov, "Research of the Possibility of Hidden Embedding of a Digital Watermark Using Practical Methods of Channel Steganography," *Studies in Computational Intelligence*, no. 868, pp. 203-209, 2020.
- [87] P. I. Sharikov, A. V. Krasov and V. N. Volkogonov, "A Study of the Correctness of the Execution of a Class File with an Embedded Digital Watermark in Different Environments," *IOP Conference Series: Materials Science and Engineering*, vol. 862, no. 5, article number 052052, 2020.
- [88] J. MacHac, V. Kaloshin, D. Kholodnyak, M. Prokhorov and T. Shevgunov, "Visit of the MTT-S Regional Coordinator to Russia [Around the Globe]," *IEEE Microwave Magazine*, vol. 21, no. 2, pp. 105-107, 2020.
- [89] O. Semeshko, M. Pasichnyk, L. Hyrlya, V. Vasylenko and E. Kucher, "Studying the Influence of UV Adsorbers on Optical Characteristics of Light-Protective Polymer Films for Textile Materials," *Eastern-European Journal of Enterprise Technologies*, vol. 3, no. 6-99, pp. 14-21, 2019.
- [90] M. Pasichnyk, E. Kucher and L. Hyrlya, "Synthesis of Magnetite Nanoparticles Stabilized by Polyvinylpyrrolidone and Analysis of Their Absorption Bands," *Eastern-European Journal of Enterprise Technologies*, vol. 3, no. 6-93, pp. 26-32, 2018.
- [91] A. M. Tatenov and S. M. Askarova, "Virtual and Interactive Information Technology in Modeling of Educational Processes and in Modeling, Researches of Processes of Applied Problems of a Science," *World Applied Sciences Journal*, vol. 30, no. 30, pp. 144-148, 2014.
- [92] G. M. Grigorenko, L. I. Adeeva, A. Y. Tunik, V. N. Korzhik, L. K. Doroshenko, Y.P. Titkov and A.A. Chaika, "Structurization of Coatings in the Plasma Arc Spraying Process Using B4C + (Cr, Fe)7C3-Cored Wires," *Powder Metallurgy and Metal Ceramics*, vol. 58, no. 5-6, pp. 312-322, 2019.
- [93] Y. M. Koval, V. Z. Kutsova and M. A. Kovzel, "Regularities of Formation of Structure, Phase Composition and Properties of Chromium–Manganese Alloys in the Initial Cast State During the Process of Friction Wear," *Metallofizika i Noveishie Tekhnologii*, vol. 43, no. 3, pp. 407-423, 2021.
- [94] V. Z. Kutsova, A. V. Zhivotovich, M. A. Kovzel and A. V. Kravchenko, "Structure, Phase Composition and Phase X-Ray Spectroscopic Analysis of High-Temperature Chromium-Nickel Alloy," *Metallofizika i Noveishie Tekhnologii*, no. 30(SPEC. ISS.), pp. 235-243, 2008.
- [95] M. Pasichnyk and E. Kucher, "A Mathematical Modeling of Crosslinking Between Components of a Polymer Composition," *Eastern-European Journal of Enterprise Technologies*, vol. 2, no. 6, pp. 4-12, 2016.
- [96] T. Y. Shevgunov, "The Development of Fast Algorithm for Continuous-Time Subsectional Polynomial E-Pulse Synthesis," *TEM Journal*, vol. 9, no. 3, pp. 881-888, 2020.