Advances in Science and Technology
ISSN: 1662-0356, Vol. 156, pp 127-136
doi:10.4028/p-5aAMEf

Submitted: 2024-03-29
Accepted: 2024-05-18
Online: 2024-09-09

Computer Modelling of the Process of Separation of Heterogeneous Elements (Spheres)

PASTERNAK Viktoriya[1,a*], RUBAN Artem[2,b], HORBACHENKO Yurii[3,c] and VAVRENIUK Sergii[4,d]

[1]Lesya Ukrainka Volyn National University, Voli Avenue 13, Lutsk, Ukraine, 43025

[2]Lviv State University of Life Safety, Kleparivska str., 35, Lviv, Ukraine, 79007

[3]Cherkassy institute of Fire Safety named after Chernobyl Heroes of National University of Civil Defence of Ukraine, Onoprienko str., 8, 18034 Cherkasy, Ukraine

[4]National University of Civil Defence of Ukraine, 94 Chernishevska str., Kharkiv, Ukraine, 61023

[a]Pasternak.Viktoriia@vnu.edu.ua, [b]a.ruban@ldubgd.edu.ua, [c]horbachenko_yurii@chipb.org.in, [d]sergii-vavrenyuk@nuczu.edu.ua

Keywords: separation, modelling, spheres, element dynamics, Liapunov's indices, correlation dependencies, physical and mechanical parameters, system.

Abstract. This scientific study considers the results of a computer experiment with heterogeneous elements (spheres) that proved to be of decisive importance during the separation process, namely their degree of activity, mobility and falling. It has been found that a detailed analysis of the Liapunov function indices allows to effectively understand and predict the dynamics of complex dynamical systems. The results obtained indicate significant changes in the physical and mechanical parameters of spherical balls under the influence of various factors and the environment. It was found that a certain accumulation of spheres occurs due to an increase in the time for simulation. It was also found that the key characteristics of the bulk mass of spherical elements significantly depend on the moulding process, surface condition and environmental conditions.

1 Introduction

Non-homogeneous elements, in particular spheres, can be considered as heterogeneous suspensions or mixtures of various components of any materials [1, 2]. In our context, spheres are individual particles or heterogeneous elements in a heterogeneous medium (heterogeneous system) [3, 4, 5]. In particular, spheres are circular heterogeneous particles that can be solid objects or elements that have the shape of a sphere (i.e., a circle) [6, 7, 8]. It should be noted that such elements are geometric bodies in which all points of the surface are equal in distance from a central point called the centre of the sphere [9, 10, 11]. Spherical particles are often used as a model for studying various physical and chemical phenomena in scientific research, and they are widely used in various fields [12, 13, 14].

The study of spherical particles is a mathematically convenient approach for analysis and computer modelling [15, 16, 17]. In some cases, when a circular element or object can be approximated by a sphere shape, it simplifies calculations and solving various problems [18, 19, 20]. For example, in our case, we study elements with spherical particles and the process of their separation. Modelling of such particles with a detailed study of separation can be used to analyse their behaviour, properties, and interaction in a heterogeneous system. One possible approach is to consider a heterogeneous system as a set of spheres with different physical and mechanical characteristics. Such a system may include spheres with different sizes, densities, hardnesses, shape factors, coordination numbers, etc. In order to model the separation process for such a heterogeneous system, we need to take into account the various physical and mechanical parameters of each individual sphere (element), as well as their interaction during the separation process.

Therefore, the development of an adequate and universal physical and mathematical model for such a heterogeneous system of sphere research with a combination of computer modelling includes elements of the theory of distributed placement, medium mechanics and various interactions between spheres. It should be noted that taking into account such a large number of factors requires the use of numerical methods and computer simulations to obtain high-quality and reliable approximation solutions. It should also be noted that such an approach will allow us to take into account the diversity of components in a heterogeneous system and their interaction, which is important for understanding and optimising the processes of separation of heterogeneous media.

The relevance of the topic lies in the fact that the study of computer modelling of heterogeneous systems represented by spherical particles is of great practical importance in various fields, such as modelling, industry, science and medicine. Taking into account heterogeneities in the form of spheres can be key to understanding and improving the separation processes of any materials. Thus, the study of the interaction and separation of inhomogeneous systems consisting of spherical particles requires partial improvement, as it has wide practical applications and can lead to important scientific and technological discoveries.

2 Main part

In the literature [21, 22, 23], spheres are considered as heterogeneous elements or particles in a heterogeneous medium. It has been shown that they can be solid objects that have the shape of a sphere. Also, the basic boundary conditions that need to be set in the simulation are partially covered. In [24, 25, 26], it was investigated that spheres are geometric bodies in which all surface points are equal to the distance from the centre point of the circle, i.e., the centre of the sphere. An analysis of works [27, 28, 29] has shown that spherical elements are often used as a model for studying various physical and chemical phenomena in scientific research. However, it is unclear in which fields the authors intended to use this approach. Papers [30, 31, 32] substantiate the study of mainly spherical particle shapes, and also highlight mathematical approaches, analysis and simulation of computer modelling with the possibility of approximating round elements. Research teams [33, 34, 35] describe experiments that take into account the main parameters, such as size, density, shape and hardness, which is important for the filling simulation process. It should be noted that the analysis of literature sources well defines the areas of research, methodology and practical significance of the study and justification of spherical elements in heterogeneous systems, while requiring minor improvement. Therefore, the study of the process of separation of inhomogeneous elements (spheres) based on computer modelling [36, 37, 38] is an urgent issue.

The aim of the study is to investigate the process of separation of spheres (elements) on the basis of computer modelling [39, 40, 41], as well as to analyse the dynamics of a system that includes separated spherical elements and determine the main factors that affect their behaviour.

Materials. The process of separation of heterogeneous elements, namely spheres, is the procedure of separating or extracting spherical particles from a heterogeneous system based on certain characteristics of the particles or the medium. This process may involve the use of a variety of methods and approaches to separate spherical elements [42, 43] from other components of the system. For example, a separation procedure may include filtration, centrifugation, sedimentation, or other methods aimed at separating spherical objects from other components of a heterogeneous system.

For the effective implementation of computer and numerical modelling, a number of physical and mechanical characteristics of heterogeneous elements (spheres) were taken into account. Among them, it is worth noting the Young's modulus of 0.1 MPa, the Poisson's ratio of 0.7, and the friction coefficient of 0.5. The volume mass of the spherical elements was in the range of 100 to 300 kg/m^3. Also, the parameters of the heterogeneous medium were taken into account, in particular, the falling velocity, dynamic viscosity, average coordination number, Prandtl's coefficient of 0.4, etc. In addition, to ensure the accuracy of the numerical analysis, the grid cell size for the simulation was set to 0.01 mm. It should be noted that this approach is aimed at ensuring a reliable and accurate representation of physical phenomena in a heterogeneous environment system, allowing for reliable computer modelling results.

Figure 1 shows the results of a computer experiment of sphere separation, taking into account the main physical and mechanical parameters.

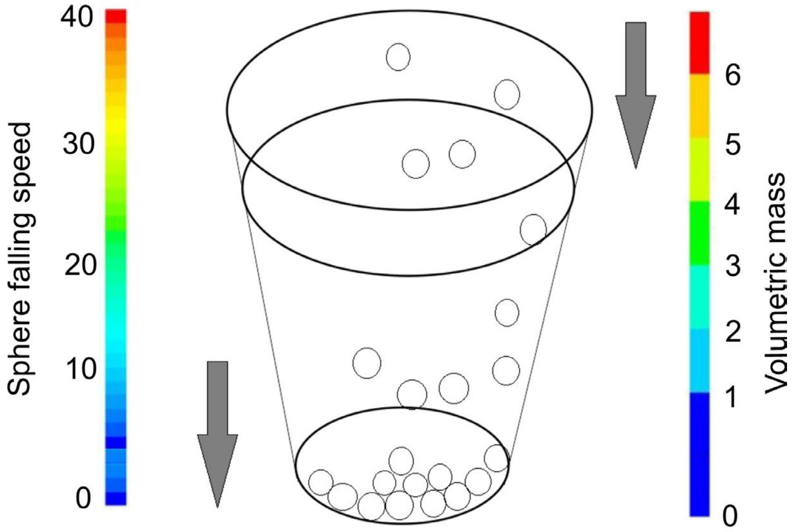

Fig. 1. Computer experiment of sphere separation taking into account the main physical and mechanical parameters

It should be noted that the total number of experiments in the field of numerical and computer modelling was 9. In the process of evaluating the quality of the separation process of heterogeneous elements (spheres), the mass distribution of components was used by two indicators:

1) by volume mass at the outputs of heavy elements, which was denoted by the symbol ρ (v);
2) by volume mass at the outputs of light components, which was denoted by the symbol ρ (l).

During the experiment, it was found that during the analysis and simulation of the data elements, an important task arises – to identify the dependencies of the concentration of sphere components on the volume mass ρ in general, as well as on the volume mass of heavy ρ (v) heterogeneous elements and light ρ (l) sphere components in the context of various factors of computer modelling.

Figure 2 shows the developed computational scheme of the process of separation and movement of heterogeneous elements (spheres) based on modelling.

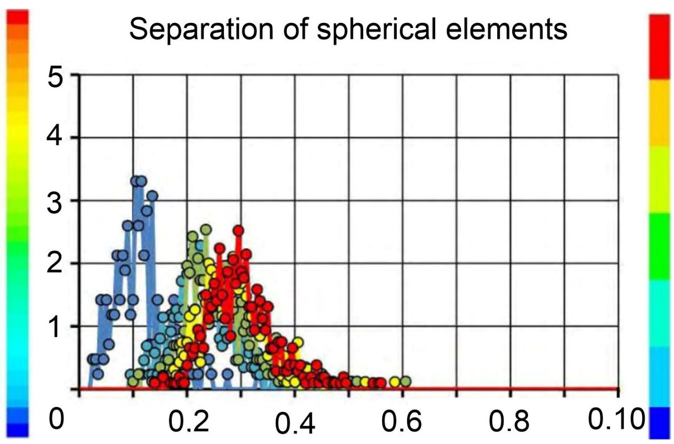

Fig. 2. Schematic of the process of separation and movement of heterogeneous elements (spheres) based on a computer experiment

It should be noted that as for the first stage of numerical modelling, a computational scheme was developed to study in detail the process of movement of falling heterogeneous particles, which occurs mainly under the influence of external factors. The developed computational scheme also includes complex aspects that are oriented and focused on the procedure of interaction of round particles with a heterogeneous medium, i.e., the minimum and maximum fall of spheres, their movement and their qualitative distribution in the system.

The proposed scheme for a detailed study of the process of movement and separation of falling heterogeneous particles (in particular, spheres) shows that more attention should be paid to the coefficients of mass distribution of spherical elements. In particular, this applies to the volumetric mass of heterogeneous elements at the outlets, i.e. ρ (v) and ρ (l). We also found out that the actual diameter of the spheres D (s) plays an important role.

Tests. To determine the detailed mass distribution of spherical elements in a heterogeneous system, we used one of the mathematical algorithms, the Frank-Wolfe algorithm. The Frank-Wolfe algorithm is a numerical method for solving optimisation problems. It is used to find the minimum or maximum of a function that can be differentiable or undifferentiable. It should be noted that this algorithm belongs to the class of qualitative optimisation methods, which is based on a combination of the methods of anchor points and projection methods. The main idea of our algorithm is that it uses successive projections on convex sets to approximate the optimum points. The implementation of the desired functions is a complex process and has certain limitations, but it can be easily achieved by computer modelling. That is, we consider a situation with two trajectories of the volume mass of heterogeneous elements at the outputs ρ (v) and ρ (l), which are separated by a small distance from each other $R_0 = \varepsilon$. After a certain time interval δ (t), these trajectories reach a value in the heterogeneous system equal to R_1. For each step, the maximum Liapunov exponent was determined according to the following mathematical formula:

$$\lambda = \log\left|r / r\right| / \delta(t) \tag{1}$$

It should be noted that as the calculation time increases, the coefficient of the Liapunov exponent approaches the real value, and in this case, we can determine the stability and instability of the dynamic system. It should be noted that as the duration of the Liapunov coefficient calculation increases, its value adapts to the actual dynamics of the system, providing more accurate results. This approach allowed us not only to determine the stability of the system at a certain point in time, but also to take into account its evolution with changes in parameters or initial conditions. Such an analysis proved to be extremely useful in modelling and predicting the behaviour of systems under different conditions. It is important to note that the accuracy of the results depends heavily on the correct choice of calculation parameters and consideration of the system's characteristics. To implement this approach, we investigated the effect of the bulk mass of heterogeneous elements on the diametric size of the elements (spheres). The system under consideration is described by a separate function, to which the main parameters of the spheres and the system, the initial values of the variable parameters, and the calculation time are passed. It should be noted that the body of this function defines mainly the parameters of the right-hand side and the Jacobian determinants of the matrix of the heterogeneous system, which are used to form equations in certain variations. As a result of our computer studies, we have obtained the following dynamics of Liapunov's indicators, which is shown in Figure 3.

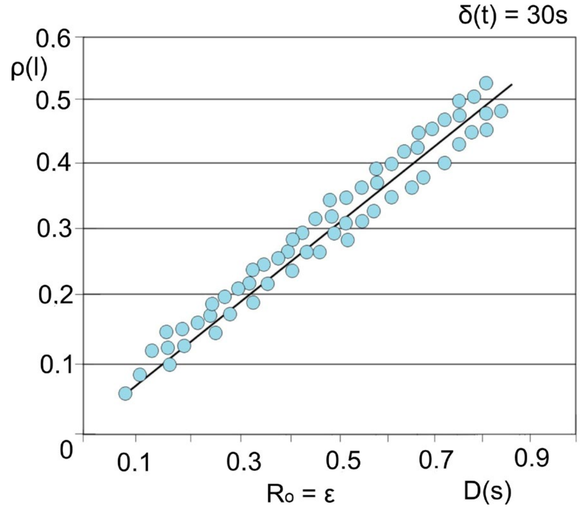

Fig. 3. Scalar indices of the mass distribution of heterogeneous elements from diametrical size of elements (spheres)

It should be emphasised that the volume mass of the lightweight components ρ (l) varied from 0 to 0.6 kg/m^3 and the study lasted for 30 seconds at a remote distance from each other according to the system $R_0 = \varepsilon$. In turn, the diameter size of the components was 0.1-0.9 mm. The results obtained show that the degree of activity and mobility of spherical elements is important. It is worth emphasising that such a detailed analysis of the Liapunov function indices can serve as a powerful tool for understanding and predicting the dynamics of complex dynamic systems. Also, the obtained dependence of scalar products shows that under the influence of various factors and the environment, some physical and mechanical parameters of spherical balls can change significantly.

Figure 4 shows the active dynamics of computer modelling indicators within the experimental study time of 60 seconds.

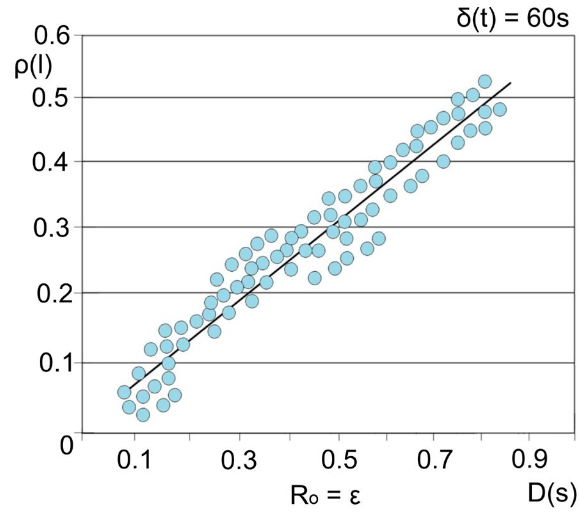

Fig. 4. Dynamics of indicators of mass distribution of heterogeneous elements from size of elements (spheres) during δ (t)=60 seconds

It should be noted that the mass of the light components ρ (l) varied from 0 to 0,6 kg/m^3, the radius of the spheres varied from 0.1 mm to 0.9 mm, the experiment time lasted 60 seconds, and the heterogeneous system was constant and equal to $R_0 = \varepsilon$. The results show a much larger accumulation of spherical elements along the correlation curve. However, the spheres interact well with each other and the environment, and their accumulation is explained by the fact that more time was allocated for the experiment – 60 seconds.

Figure 5 shows the volumetric mass of the heavy sphere elements ρ (v), which varied from 0 to 6 kg/m^3, the simulation duration was 30 seconds, the size of the spheres varied from 0.1 mm to 0.9 mm, and the system operated within the range of $R_0 = \varepsilon$.

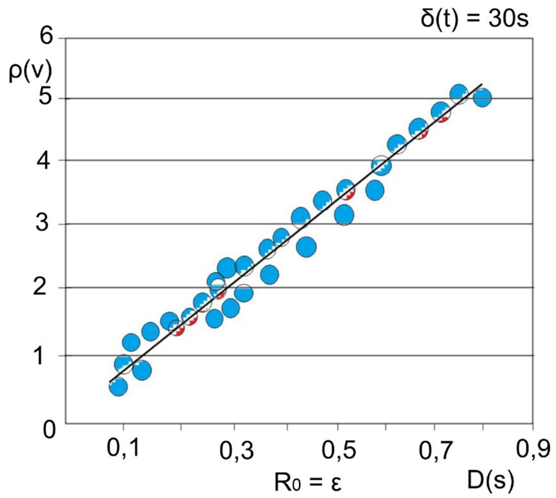

Fig. 5. Dynamics of the volumetric distribution of the mass of heavy heterogeneous elements ρ (v) from on the size of elements (spheres) during δ (t)=30 seconds

The obtained results of the volumetric mass distribution of heavy spheres of heterogeneous elements show that at a heavier bulk mass, the particles (spheres) also interact well with each other, but in this study we observed the separation of a small overlap of spheres on top of each other. This is most likely due to the quantitative distribution of heterogeneous elements by size. And also, by the length of time for computer modelling. It should also be noted that the main characteristics of the bulk mass of such heterogeneous spheres significantly depend on the process of its formation, the state of the surface of spherical particles, the conditions of movement and fall, as well as other factors.

Figure 6 shows again the bulk mass of heavy element spheres ρ (v). It should be noted that the variation in the diameter dimensions of the spherical components was 0.1–0.9 mm, the volume mass was 0–6 kg/m^3, the experiment time was 60 seconds, and the inhomogeneous environment of the system was within the range of $R_0 = \varepsilon$.

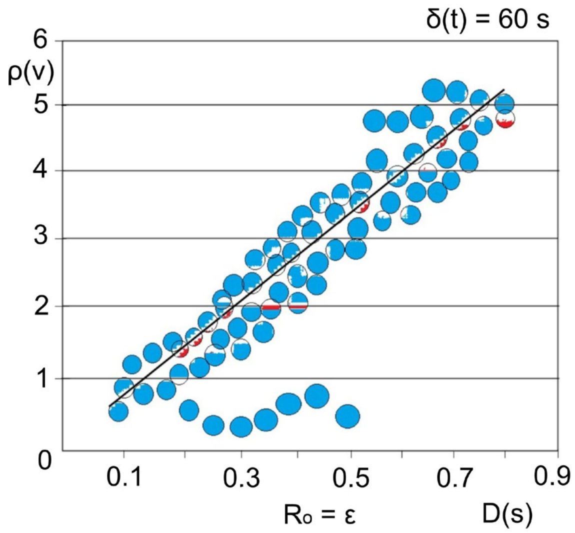

Fig. 6. The dynamics of the mass distribution of heavy heterogeneous elements, determined by the function ρ (v) with respect to their size (spherical), during a time interval δ (t) equal to 60 seconds

The results obtained show a qualitative process of separation of spheres according to their bulk mass and size variation. It should also be noted that the size of the spherical elements, in particular their radius (denoted as D (s)), is a critical and important factor in determining the contact surface area and volume. It is important to note that the mass of heavy elements or spheres has significant potential and has a much larger surface area and volume. On the other hand, a large volume can also increase the time required for numerical calculations. Thus, the choice of the optimal size of the spheres (spherical elements), taking into account their radius, depends on the specific application and requirements of the field of application, as well as on the needs and environmental effects of the heterogeneous system.

3 Conclusion

The results obtained indicate that the degree of activity and mobility of spherical elements is of great importance in a computer experiment. A detailed analysis of the Liapunov function indices can serve as an effective tool for understanding and predicting the dynamics of complex dynamical systems. The obtained dependences of scalar products show that the physical and mechanical parameters of spherical balls can change significantly under the influence of various factors and the environment.

Also, the generalised conclusions indicate that the volume mass of light components ρ (l), which varied from 0 to 0.6 kg/m^3 with a sphere radius of 0.1 mm to 0.9 mm and an experiment duration of 60 seconds under steady-state conditions, indicates some accumulation of spherical elements. This separation process is explained by the allocation of more time for the experiment – 60 seconds.

The volumetric mass distribution of the heavy spheres of heterogeneous elements indicates their interaction, but separation is observed when the size and duration of the experiment are analysed in detail. It should be noted that the main characteristics of the bulk mass of spherical elements significantly depend on the formation process, surface condition, and environmental conditions. The results also emphasise the qualitative separation of spheres according to their bulk and size. The size of the spheres, in particular their radius, determines the contact surface and volume and is a critical factor in selecting the optimum size for a particular application and system requirements. It is important to keep in mind that the mass of heavy elements or spheres has a significant potential and depends on their volume and surface area. When selecting the size of the spheres, the specific conditions and requirements, as well as the influence of the environment in a heterogeneous system, should be taken into account.

References

[1] Yi. He, Ali Hassanpour, Andrew E. Bayly, Linking particle properties to layer characteristics: Discrete element modelling of cohesive fine powder spreading in additive manufacturing. Additive Manufacturing. 36 (2020) 1–15.

[2] Jun. Wang, Zh. Zhang, F. Han, Sh. Chen, W. Ying, Modeling of laser power attenuation by powder particles for laser solid forming. ScienceDirect / Procedia CIRP. 95 (2020) 42–47.

[3] Deb. Apurba Kanti, P. Chatterjee, Study of deformation microstructure of nickel samples at very short milling times: effects of addition of α-Al2O3 particles. Journal of Theoretical and Applied Physics. 13 (2019) 63-73.

[4] A. Ruban, V. Pasternak, N. Huliieva, Prediction of the structural properties of powder materials by 3D modeling methods. Materials Science Forum. 1068 (2022) 231–238. https://doi.org/10.4028/p-18k386

[5] Sh. Seyfi, B. Mirzayi, H. Seyyedbagheri, CFD modeling of black powder particles deposition in 3D 90-degree bend of natural gas pipelines. Journal of Natural Gas Science and Engineering. 78 (2020) 1–20.

[6] Z. Zhang, X.X. Yao, P. Ge, Phase-field-model-based analysis of the effects of powder particle on porosities and densities in selective laser sintering additive manufacturing. International Journal of Mechanical Sciences. 166 (2020) 1–15.

[7] V. Pasternak, L. Samchuk, N. Huliieva, I. Andrushchak, A. Ruban, Investigation of the properties of powder materials using computer modeling. Materials Science Forum. 1038 (2021) 33–39. https://doi.org/10.4028/www.scientific.net/MSF.1038.33

[8] Ch. Liang, Yan. Yin, Wen. Wang, A thermodynamically consistent non-isothermal phase-field model for selective laser sintering. International Journal of Mechanical Sciences. 166 (2023) 1–15.

[9] Xin. Chu, Han. Che, Ch. Teng, Ph. Vo, St. Yue, A multiple particle arrangement model to understand cold spray characteristics of bimodal size 316L/Fe powder mixtures. Surface and Coatings Technology. 381 (2020) 1–23.

[10] H. Sulym, Ia. Pasternak, V. Pasternak, Boundary element modeling of pyroelectric solids with shell inclusions. Mechanics and Mechanical Engineering. 22 (2018) 727–737. https://doi.org/10.2478/mme-2018-0057

[11] V. Pasternak, A. Ruban, M. Surianinov, Yu. Otrosh, A. Romin, Software modeling environment for solving problems of structurally inhomogeneous materials. Materials Science Forum. 1068 (2022) 215–222. https://doi.org/10.4028/p-h1c2rp

[12] Zh. Han, Ping-X. Zhang, Li-Ming. Lei, Shu-J. Liang, Qing-X. Wang, Yun-J. Lai, Jin-Sh. Li, Morphology and particle analysis of the Ni3Al-based spherical powders manufactured by supreme-speed plasma rotating electrode process. Journal of Materials Research and Technology. 9 (2020) 13937–13944.

[13] Yang. Liu, Xiao-h. Zhao, Yun-jin. Lai, Qing-xiang. Wang, Li-Ming. Lei, Shu-jin. Liang, A brief introduction to the selective laser melting of Ti6Al4V powders by supreme-speed plasma rotating electrode process. Progress in Natural Science: Materials International. 30 (2020) 94–99.

[14] O. Blyznyuk, A. Vasilchenko, A. Ruban, Y. Bezuhla, Improvement of fire resistance of polymeric materials at their filling with aluminosilicates. Materials Science Forum. 1006 (2020) 55–61.

[15] E.M. Both, R.M. Boom, M.A.I. Schutyser, Particle morphology and powder properties during spray drying of maltodextrin and whey protein mixtures. Powder Technology. 363 (2020) 519–524.

[16] Z. Lin, L. Tian-Shu, D. Tao-Tao, L. Tao-Tao, Q. Feng, Y. Hong-Yu, Design of a new Al-Cu alloy manipulated by in-situ nanocrystals withsuperior high temperature tensile properties and its constitutive equation. Materials and Design. 181 (2019) 1–12.

[17] V. Pasternak, A. Ruban, M. Surianinov, S. Shapoval, Simulation modeling of an inhomogeneous medium, in particular: round, triangular, square shapes. Defect and Diffusion Forum. 428 (2023) 27–35. https://www.scientific.net/DDF.428.27

[18] Sunday A. Afolalu, Olusegun D. Samuel, Omolayo M. Ikumapayi, Development and characterization of nano- flux welding powder from calcined coconut shell ash admixture with FeO particles. Journal of Materials Research and Technology. 9 (2020) 9232–9241.

[19] N. Yumak, K. Aslantas, A review on heat treatment efficiency in metastable β titanium alloys: the role of treatment process and parameters. Journal of materials research and technology. 9 (2020) 15360–15380.

[20] V. Pasternak, A. Ruban, V. Hurkalenko, A. Zhyhlo, Computer simulation modeling of an inhomogeneous medium with ellipse-shaped irregular elements. Defect and Diffusion Forum. 428 (2023) 37–45. https://www.scientific.net/DDF.428.37

[21] V. Venkatesh, R. Noraas, A. Pilchak, S. Tamirisa, K. Calvert, A. Salem, T. Broderick, M. Glavicic, I. Dempster, V. Saraf, Data driven tools and methods for microtexture classification and dwell fatigue life prediction in dual phase titanium alloys. Web of Conferences. 321 (2020) 1–8.

[22] S. Smirnov, L. Zamaraev, Comparative study of Shot creep of single-phase titanium alloys in air and neutral gas environment on the test temperature in range from 673 to 1323 K. Frattura ed Integrità Strutturale. 49 (2019) 201–211.

[23] V. Pasternak, A. Ruban, N. Zolotova, O. Suprun, Computer modeling of inhomogeneous media using the Abaqus software package. Defect and Diffusion Forum. 428 (2023) 47–56. https://www.scientific.net/DDF.428.47

[24] A. Sharshanov, O. Tarakhno, A.M. Babayev, O. Skorodumova, Mathematical Modeling of the Protective Effect of Ethyl Silicate Gel Coating on Textile Materials under Conditions of Constant or Dynamic Thermal Exposure. Key Engineering Materials. 927 (2022) 77–86. https://doi.org/10.4028/p-8t33rc

[25] Tin. Peng, Yin. Shi, Ch. Zhu, D. Feng, Xi. Ma, Peipei. Yang, Xueq. Bai, Xin. Pan, Chuan-yu. Wu, Wen. Tan, Chuan. Wu, Data on the drug release profiles and powder characteristics of the ethyl cellulose based microparticles prepared by the ultra-fine particle processing system. Data in brief. 29 (2020) 1–6.

[26] I. Ryshchenko, L. Lyashok, A. Vasilchenko, A. Ruban, L. Skatkov, Electrochemical synthesis of crystalline niobium oxide. Materials Science Forum. 1038 (2021) 51–60. https://doi.org/10.4028/www.scientific.net/MSF.1038.51

[27] Z. Lin, L. Tian-Shu, D. Tao-Tao, L. Tao-Tao, Q. Feng, Y. Hong-Yu, Design of a new Al-Cu alloy manipulated by in-situ nanocrystals withsuperior high temperature tensile properties and its constitutive equation. Materials and Design. 181 (2019) 1–12.

[28] Sh. Balachandran, A. Tripathi, Ar. Banerjee, M. Chinara, R. Teja, S. Suresha, D. Choudhuri, R. Banerjee, D. Banerjee, Transformations, recrystallization, microtexture and plasticity in titanium alloys. Web of Conferences. 321 (2020) 1–13.

[29] V. Pasternak, A. Ruban, V. Shvedun, J. Veretennikova, Development of a 3d computer simulation model using C++ methods. Defect and Diffusion Forum. 428 (2023) 57–66. https://www.scientific.net/DDF.428.57

[30] Xin. Xu, I. Bantounas, D. Dye, Deformation behaviour of beta phase with similar chemical composition in beta and alpha + beta titanium alloys. Web of Conferences. 321 (2020) 1–5.

[31] V. Venkatesh, R. Noraas, A. Pilchak, S. Tamirisa, K. Calvert, A. Salem, T. Broderick, M. Glavicic, I. Dempster, V. Saraf, Data driven tools and methods for microtexture classification and dwell fatigue life prediction in dual phase titanium alloys. Web of Conferences. 321 (2020) 1–8.

[32] A. Vasilchenko, O. Danilin, T. Lutsenko, A. Ruban, D. Nestorenko, Features of some polymer building materials behavior at heating. Materials Science Forum. 1006 (2020) 47–54.

[33] Joseph W. Roberts, Christopher J. Sutcliffe, Peter L. Green, Kate Black, Modelling of metallic particle binders for increased part density in binder jet printed components. Additive Manufacturing. 34 (2020) 1–9.

[34] Quan. Huang, We. Zhou, Gan. Ma, Tang-T. Ng, Kun. Xu, Experimental and numerical investigation of Weibullian behavior of grain crushing strength. Geoscience Frontiers. 11 (2020) 401–411.

[35] V. Pasternak, H. Sulym, I.M. Pasternak, Frequency domain Green's function and boundary integral equations for multifield materials and quasicrystals. International Journal of Solids and Structures. 286–287 (2024) 112562. https://doi.org/10.1016/j.ijsolstr.2023.112562

[36] Jun-bao. Li, Wei-bing. Li, Xiao-ming. Wang, Wen-bin Li, Shock response and prediction model of equation of state for aluminum powder/rubber matrix composites. Materials and Design. 191 (2020) 1–10.

[37] O. Mirgorod, G. Shabanova, A. Ruban, V. Shvedun, Experiment planning for prospective use of barium-containing alumina cement for refractory concrete making. Materials Science Forum. 1038 (2021) 330–335. https://doi.org/10.4028/www.scientific.net/MSF.1038.330

[38] L. Zhang, L. Guangfu, Mathematical modeling for ceramic shape 3d image based on deep learning algorithm. Advances in Mathematical Physics. 1 (2021) 1–10.

[39] Xu. Xiaohuan, S. Jianjun, X. Rongxi, Finite element stress model of direct band gap ge implementation method compatible with Si process. Advances in Condensed Matter Physics. 1 (2021) 1–10.

[40] N. Chopenko, V. Muravlev, O. Skorodumova, Technology of molding masses for architectural and artistic ceramics using low-aluminate clays. International Journal of Engineering and Technology(UAE). 7(3) (2018) 587–5906.

[41] V. Pasternak, L. Samchuk, A. Ruban, O. Chernenko, N. Morkovska, Investigation of the main stages in modeling spherical particles of inhomogeneous materials. Materials Science Forum. 1068 (2022) 207–214. https://doi.org/10.4028/p-9jq543

[42] O. Skorodumova, O. Tarakhno, A.M. Babayev, A. Chernukha, S. Shvydka, Study of Phosphorus-Containing Silica Coatings Based on Liquid Glass for Fire Protection of Textile Materials. Key Engineering Materials. 954 (2023) 167–175. https://doi.org/10.4028/p-hgyq9v

[43] S.M. Logvinkov, I.A. Ostapenko, O.N. Borisenko, O.B. Skorodumova, A.A. Ivashura, Prediction of melting paths of wollastonite-containing compositions. China's Refractories. 29(3) (2020) 13–18.