ABSTRACTS

INTERNATIONAL SUMMER SCHOOL CONFERENCE ADVANCED PROBLEMS IN MECHANICS

St. Petersburg 2022

POLYTECH Peter the Great St.Petersburg Polytechnic University
Russian Academy of Sciences
ИПМАШ Российская академия наук
Министерство науки и высшего образования Российской Федерации
Газпром нефть | Научно-технический центр

L International Conference
“Advanced Problems in Mechanics”

June 20-24, 2022,
St. Petersburg, Russia

APM 2022
BOOK OF ABSTRACTS

POLYTECH
Peter the Great
St.Petersburg Polytechnic
University

IPME RAS

www.apm-conf.spb.ru

HARD PHASE AND SOFT PHASE REACTIONS IN MEMORY BEHAVIOUR OF SHAPE MEMORY ALLOYS

Adiguzel O.
Firat University, Department of Physics, Elazig, Turkey
oadiguzel@firat.edu.tr

Some materials take place in class of smart materials with adaptive properties and stimulus response to the external changes. Shape memory alloys take place in this group, by exhibiting a peculiar property, called shape memory effect. High temperature phases of these alloys are hard phase, low temperature phases are soft phase, and these alloys exhibit two behavior, thermoelasticity and superelasticity, from viewpoint of reversibility. Shape memory effect is initiated by thermomechanical treatments with cooling and deformation and performed thermally on heating and cooling, with which, shape of material cycles thermally between the deformed and original shapes. Therefore, this behaviour can be called thermoelasticity. This is plastic deformation, due to the soft character of the alloy in low temperature condition, strain energy is stored in the materials, and released on heating by recovering the original shape. These alloys exhibit another property called superelasticity, which is performed mechanically stressing and releasing in elasticity limit at a constant temperature at hard parent phase region. Shape recovery occurs instantly and simultaneously upon releasing, by exhibiting elastic material behaviour. Stress-strain profile exhibit nonlinear behaviour, at the stress-strain profile, stressing and releasing paths are different, and hysteresis loop refers to energy dissipation. It means that even if stressing is quick, releasing is slow, and these materials are used in building and bridge industry, against seismic events. Shape memory effect is governed by the thermal and mechanical reactions, thermal and stress induced martensitic transformations. Thermal induced martensitic transformation occurs on cooling with the cooperative movement of atoms in <110>-type directions on {110}-type planes of austenite matrix, by means of shear-like mechanism, along with lattice twinning, and ordered parent phase structures turn into twinned martensite structures. Twinned martensite structures turn into detwinned martensite structures by means of stress induced transformation by stressing material plastically in martensitic condition. Superelasticity is also result of stress induced martensitic transformation and ordered parent phase structures turn into detwinned structure with stressing. Copper based alloys exhibit this property in metastable β-phase region, which has bcc-based structures. Lattice invariant shears and lattice twinning are not uniform in these alloys, and cause to formation of the non-conventional layered structures with martensitic transformation. The long-period layered structures can be described by different unit cells as 3R, 9R or 18R depending on the stacking sequences on the close-packed planes of the parent phase.
In the present contribution, x-ray diffraction and transmission electron microscopy studies were carried out on copper based CuZnAl and CuAlMn alloys. X-ray diffraction profiles and electron diffraction patterns exhibit super lattice reflections inherited from parent phase. X-ray diffractograms taken in a long-time interval show that diffraction angles and intensities of diffraction peaks change with the aging time at room temperature, and this result refers to a new transformation in diffusive manner.

SCALING ANALYSIS FOR A 3-D CO_2 PLUME IN A SLOPING AQUIFER AT A LATE STAGE OF INJECTION

Afanasyev A.A., Vedeneeva E.A., Grechko S.S.
Institute of Mechanics, Moscow State University, Moscow, Russia
afanasyev@imec.msu.ru

Utilization of CO_2 in saline aquifers is widely acknowledged as a viable technique to mitigate the effect of climate change by reducing the greenhouse gas emissions into the atmosphere. The utilization can be implemented by a few wells used to inject CO_2 into a confined aquifer overlain by a caprock. The injection leads to the formation of CO_2 plume mostly caused by the buoyancy-driven gas flow. The less denser gas, as compared to brine, rises to the upper parts of the aquifer and spreads below impermeable caprock. The modeling of the gas transport in the plume with account for all trapping mechanisms is very important for evaluating the consequences and potential risks of the utilization. A potential risk of the injection is the leakage through old, abandoned wells or faults near the injection site. If the injection occurs into a large regional sloping aquifer without a structural trap, then gas can reach much more distant areas from the injection site than in the case of injection into an anticline reservoir. In a negative scenario, the old wells and faults can serve as potential paths for gas to the Earth surface. The leakage can result in groundwater pollution or, in the case of the leakage to the atmosphere, makes the utilization worthless.
To assess the noted risk of leakage we investigate supercritical CO_2 injection into a sloping saline aquifer and propose a simple relationship to estimate the maximum gas migration distance in the updip direction. This might be the most hazardous direction to a leakage site. The proposed estimate is derived from the system of governing equations for immiscible flow of gas and formation brine. By writing the equations in non-dimensional form, we guess the scaling law for the migration distance at a late stage of CO_2 injection. Then, we verify the scaling law by means of 3-D reservoir simulations of miscible CO_2 injection with account for the residual and solubility trapping. We derive an estimate that relates the maximum migration distance with the dip angle, the porosity, the anisotropic permeability, and

the end-points of saturation functions. We show that the estimate is rather accurate for different reservoir temperatures and brine salinity and in the case of a flue gas injection. We show that the proposed scaling is useful for a quick assessment of the risk of CO_2 reaching a potential leakage site in a large regional aquifer. It can also be applied to estimate the propagation of the uncertainties of reservoir parameters to the uncertainty of the migration distance.
We acknowledge the financial support of the Russian Science Foundation (grant no. 19-71-10051). We are also grateful to the reservoir engineers of the Gazpromneft Science and Technology Centre for fruitful discussions. Some simulation work of this study was partly funded by the Gazpromneft STC.

ADVANCED METHODS FOR SOLVING CONTACT PROBLEMS FOR AN INHOMOGENEOUS LAYER AND HALF-SPACE

Aizikovich S.M., Volkov S.S., Lapina P.A.
Don State Technical University, Rostov-on-Don, 344000, Russia
saizikovich@gmail.com

The School of Mechanics of Rostov-on-Don has developed methods for solving the so-called non-classical contact problems for a strip and a layer on a non-deformable foundation (Vorovich, I.I., Aleksandrov, V.M., Babeshko, V.A. (1974) Neklassicheskiye smeshannyye zadachi teorii uprugosti [Non-classical mixed problems of the theory of elasticity]. Nauka Publishers: Moscow. Russia. In Russ.).
To solve integral equations for both the multilayered and continuously inhomogeneous foundations, an approximate analytical (bilateral asymptotic) method was later developed. In the general case, the kernel transform of the integral equation is constructed numerically and approximated by an analytical expression of a special form. For this special form of approximation, it is possible to construct a closed solution. It is proved that this solution is bilateral asymptotically exact with respect to the values of the characteristic geometrical parameter of the problem.
In the present work, the solutions constructed by the bilateral asymptotic method and by the methods of large and small parameters, using the example of the contact problem on the shear of the surface of a half-space that is inhomogeneous by depth are compared. Two approximate models of an inhomogeneous half-space are considered. The first model considers an inhomogeneous layer on an elastic foundation. The shear modulus of the layer changes exponentially by depth up to a certain depth, and then stabilizes and becomes constant. The solution is constructed by a bilateral asymptotic method (Aizikovich, S.M. (1990) An asymptotic solution of a class of coupled equations. Journal of Applied Mathematics and Mechanics, 54(5), 719-724).
For the second model, in which the shear modulus changes by depth in the entire half-space according to an exponential law, the solution is constructed by the methods of large and small parameters, namely, by expanding in powers of the dimensionless parameter of the problem and by the Wiener-Hopf method (Zelentsov, V.B., Lapina, P.A., Mitrin, B.I., & Eremeyev, V.A. (2020) Characterization of the functionally graded shear modulus of a half-space. Mathematics, 8(4), 640).
Numerical analysis showed the existence of areas of problem parameters for which the difference between the kernel transforms of integral equations is small. For these parameters, the contact stresses for the first and second models are compared.
The bilateral asymptotic method makes it possible to obtain an approximate analytical solution of typical non-classical problems for a layer as well. An approximate model of a two-layer base is used, when the elastic properties of the coating and the substrate differ by more than a hundred times.
This research was funded by a grant from the RSF (grant № 22-49-08014).

FLUID DYNAMICS OF DISPERSED SYSTEMS: FUNDAMENTALS AND APPLICATIONS

Akhatov I.Sh.
Center for materials technologies, Skolkovo institute of science and technologies, Moscow, Russia
i.akhatov@skoltech.ru

Disperse system dynamics is a branch of mechanics covering aerosols (drops of a liquid dispersed in a gas), emulsions (drops of a liquid dispersed in another liquid), suspensions (solid particles dispersed in a gas or liquid), powders (packed porous media), and bubbly liquids (gas bubbles scattered in a liquid). Due to its practical significance, the dynamics of dispersed systems has been developed for many years by many research groups around the world and has been successfully used in Russia and abroad to solve problems in nuclear, oil, chemical, and environmental engineering.
The presentation discusses applied but fundamental problems of hydrodynamics of disperse systems relevant to industrial applications. Namely: (1) detonation in powdered explosives; (2) collapsing bubbles and sonoluminescence; (3) acoustic cavitation; (4) collimation of aerosol beams; (5) graphene heterostructures; and many others.

NUMERICAL ESTIMATION OF FATIGUE LIFE OF ALUMINUM ALLOY WITH SURFACE DEFECTS

Almazova L., Sedova O.S.
Saint Petersburg State University, Saint-Petersburg, Russia
liana.1707.la@gmail.com

Most of the metal constructions are subjected to cyclic mechanical loads during their service life. Therefore, it is important to understand how the mechanical properties of the material in question degrade as a result of the gradual accumulation of damage under the influence of various stresses, i.e. the fatigue life of the material.

For a more accurate assessment of fatigue life, it is necessary to determine the appropriate parameters of the metal in question as a result of many experiments. The resources for conducting experiments are quite limited, or it may be impossible to create the necessary conditions. Thus, the case with a zero mean stress has become the one that has been most studied experimentally. Whereas, when the magnitude of loading in both directions is different, mean stress plays a vital role in fatigue life estimation. There are variety models for the mean stress correction which allow one to use the data from experiments with zero mean stress to a case where the mean stress is non-zero.

Moreover, the majority of structures always contain a certain number of defects, which, becoming stress concentrators, reduce the strength and fatigue life of the structure. Such local stress concentrators may be induced by corrosion.

In the paper, the fatigue life of a specimen made of aluminum alloy is assessed. Fatigue life is determined by the S-N curve method. The specimen is weakened by corrosion defects. Two geometry models with defects of different shapes and two models with corresponding equivalent defects are constructed and analyzed. The mean stress correction is used to account for the effect of non-zero mean stresses.

PLATE AND SHELL THEORIES AND ZHILIN'S SPECIAL VIEW OF THEM

Altenbach H.
Institut für Mechanik, Fakultät für Maschinenbau, Otto-von-Guericke-Universität Magdeburg, Germany
holm.altenbach@ovgu.de

If we take the plate and shell theories that are currently established, we can classify them. Mathematical and engineering characteristics are common to classify the theories. All theories try to describe an originally three-dimensional problem approximately in two dimensions.

The main principle of the direct plate and shell theories is based on the fact that à priori no three-dimensional continuum is assumed. The basic equations are formulated for deformable surfaces. The concept of P.A. Zhilin, which was established in the 70's of the last century, represents a particularly consistent development of the plate and shell equations. This leads to some results, which are more correct than those of other authors.

INFLUENCE OF OIL COMPOSITION ON THE OPTIMAL STRATEGIES OF CO_2 INJECTION INTO OIL RESERVOIRS

Andreeva A.I., Afanasyev A.A.
Institute of mechanics Lomonosov Moscow State University
waandreeva@gmail.com

One of the most actual environmental problems is the emissions of greenhouse gases into the atmosphere in particular the carbon dioxide (CO_2) emissions. The carbon capture and storage (CCS) in petroleum reservoirs is often proposed as a solution to the problem. This is beneficial for both the emissions reduction and an enhanced oil recovery. Furthermore, CO_2 is also one of the associated petroleum gases to be disposed of. It is unacceptable to release associated gas into the atmosphere and its flaring is also bad for the environment. Therefore, the gas injection is more environmentally and economically profitable.

In this work we investigate the CO_2 enhanced oil recovery by means of 1-D compositional modelling with the MUFITS reservoir simulator. The formulated problem involves a porous medium saturated with oil of some composition. We employ the standard modeling approach based on balance equations for each hydrocarbon component, CO_2 and water. We use the SRK equation of state for predicting phase equilibria in the hydrocarbon mixture with CO_2. This allows for an accurate modeling of the CO_2 dissolution in the oil phase and oil evaporation into the gas phase. We consider different water-alternating-gas (WAG) injection strategies with both alternating and simultaneous water and CO_2 injection. The optimization criterion is the maximization of economic profit, i.e. the net present value (NPV). We determine the volumes of water and gas slugs at which NPV is maximum over various injection strategies. The optimal strategies can be different depending on the oil composition. We determine the relationship between the physical characteristics of the reservoir oil and the optimal strategies of CO_2 flooding. The oil density is one of the main characteristics of oil. Different petroleum compositions correspond to their own density values. The bubble-point pressure (BPP) of the oil is also one of characteristics of oil. BPP depends on the reservoir temperature and petroleum composition. We show that BPP cannot be used to characterize the optimal strategies. Therefore, we study the influence of oil density on the optimal WAG strategies. We show that the efficiency of WAG decreases with the oil density. So, WAG strategies should be applied to the reservoirs characterized with a light oil.

GENERATIVE DESIGN OF A PRECISION CALORIMETER MODEL

Andreeva T.A.[1,2], Lukin A.Ya.[2], Hvatov A.A.[1], Klimova A.K.[2], Maslyaev M.A.[1], Bykov N.Yu.[1,2]
1 - ITMO University, St. Petersburg, Russia
2 - Peter the Great St.Petersburg Polytechnic University, St.Petersburg, Russia
andreeva_ta@spbstu.ru

Maintaining a given temperature distribution in equipment that heats a test sample or industrial object is a very common task. An example would be any dynamic measurement where the heating system provides not only heat but also small temperature gradients across the sample. Although a simple PID (proportional–integral–derivative) controller can partially solve the problem, it is not optimal because it does not use information about the main source of change - the current value of the heaters power [1]. The quality of control can be significantly improved by including a model of thermal processes in the control algorithm. The temperature distribution in an operating device can be calculated from a full-fledged 3D model based on partial differential equations, but this approach has at least two drawbacks: the presence of many difficult-to-determine parameters and excessive complexity for control problems. The development of a simplified mathematical model, free from these shortcomings, makes it possible to achieve a significant improvement in the quality of control. The development of such a model is considered on the example of a precision adiabatic calorimeter designed to measure the specific heat of solids [2]. The simplest thermal model makes it possible to describe slow processes in a calorimeter quite successfully but is not suitable for transient processes. Refinement of the model using generative design methods [3] can significantly improve the agreement between calculated and experimental data.
This research is financially supported by The Russian Science Foundation, Agreement №21-11-00296, https://rscf.ru/en/project/21-11-00296/

[1] Andreeva T.A., Bykov N.Y., Vlasova, V.V. et al., Measurement Techniques, 2022, vol. 64, no. 11, pp. 903–911. https://doi.org/10.1007/s11018-022-02023-6
[2] Kompan T. A., Kulagin V. I., Vlasova V. V., et al., Measurement Techniques, 2020, vol. 63, no. 6, pp 407–413. https://doi.org/10.1007/s11018-020-01802-3
[3] Maslyaev M., Hvatov A., Kalyuzhnaya A.V., J. Comp. Sci., 2021, vol. 53, 101345. https://doi.org/10.1016/j.jocs.2021.101345

MATHEMATICAL MODELS IN PURE AND APPLIED MATHEMATICS

Andrianov I.
RWTH Aachen University, Germany
igor.andrianov@gmail.com

„Mathematics may be compared to a mill of exquisite workmanship, which grinds you stuff of any degree of fineness; but, nevertheless, what you get out depends upon what you put in; and as the grandest mill in the world will not extract wheat-flour from peascod, so pages of formulae will not get a definite result out of loose data“ (Huxley).
So, we must try to put a good grain in mathematical mills. In other words, the adequacy of the mathematical model is no less important than the correctness of the formal mathematical analysis.
The report discusses the definitions of Pure and Applied Mathematics and mathematical model, as well as the points of view on the subject of the classics - Poincaré, Lyapunov, Lord Rayleigh. Examples include problem of truncation, continualization and splashes, Navier-Stokes equations, Kirhhoff's and Bolotin's approximations.
The main conclusion can be formulated as follows. Any correct mathematical model is asymptotic. It includes as an inseparable part the asymptotic estimates and constraints on which it is based. Only in this case it is formulated quite definitely as a mathematical one.

SYNCHROTRON X-RAY STUDY AND MICROMECHANICAL INTERPRETATION OF DISLOCATION EMISSION FROM GAS CAPSULES IN SHAPED SAPPHIRE

Argunova T.S.[1], Kohn V.G.[2], Krymov V.M.[1], Gutkin M.Yu.[3,4,5]
1 - Ioffe Institute of the Russian Academy of Sciences, St. Petersburg, Russia
2 - National Research Centre "Kurchatov Institute", Moscow, Russia
3 - Institute for Problems in Mechanical Engineering, RAS, St. Petersburg, Russia
4 - Peter the Great St. Petersburg Polytechnic University, St. Petersburg, Russia
5 - ITMO University, St. Petersburg, Russia
argunova2002@mail.ru

The high demand for sapphire crystals derives from necessity to fabricate various products, such as high-power lasers, substrates for electronic devices, and different instruments, including tubes, rods, ribbons, etc. Methods of sapphire growth have their advantages and disadvantages depending on the application but do not eliminate the main similarity: sapphire crystals are grown from a gas-saturated melt. A common feature of growing crystals is the ability of the engulfment gas bubbles that occur at the solidification interface. The gas capsules formed in the crystal interior can have different shapes and sizes [1]. Obviously, the probability of their nucleation depends on the growth method. However, it is almost impossible to achieve complete elimination of the capsules. As a result, the transparency of sapphire in the visible light range decreases and its structural quality deteriorates. In particular, gas capsules can provoke the formation of lattice dislocations and weakly misoriented grains, which reduces the strength of the crystals.

In this work we focus on μm-sized spherical capsules and suggest a model for dislocation emission that takes into account the sizes of the spheres. Optical microscopy is commonly used for sizing. However, when performing high magnification optical microscopy, the reduced focus length is required to detect micro-inclusions, which limits the possibilities of visible light imaging to thin samples. A large thickness of sapphire articles, e.g., wafers, ribbons, rods, needles, *etc*., does not permit an accurate determination of the capsule size using a light microscope. Therefore we decided to take advantage of the properties of a 3rd-generation synchrotron radiation (SR) x-ray beam and to use an in-line phase-contrast imaging (PCI) technique [2].

Phase-contrast images are recorded on a charge-coupled device (CCD). In PCI technique, image features depend on the sample-to-CCD distance. Recording images at several distances one can determine the real size of the capsule by solving the inverse problem. The way to solve the inverse problem is computer simulation which is made using the program developed within the framework of the phase-contrast theory of three-dimensional objects [3].

X-ray Bragg diffraction imaging (topography) visualizes structural defects in sapphire crystals. As a result, by matching phase-contrast and diffraction images we have related the generation of dislocations to the capsules. Finally, the micromechanical interpretation to critical strains for the basal plane slip is provided.

Acknowledgment.
This research was supported by Russian Foundation for Basic Research (RFBR), grant numbers 19-29-12041 mk and 19-29-12043 mk.

References

1. Bakholdin S I, Maslov V N, and Nosov Yu G 2014 Crystallography Reports 59 762
2. Snigirev A, Snigireva I, Kohn V, Kuznetsov S and Schelokov I 1995 Rev. Sci. Instrum. 66 5486
3. Kohn V 2021. Available online: http://xray-optics.ucoz.ru/XR/xrwp.htm

THE CREEP CURVES MODIFICATION AFTER AGING FOR DIFFERENT PROGRAMS

Arutyunyan A.R.
St.-Petersburg State University
a.arutyunyan@spbu.ru

At recent decades, polymer composite materials become more widespread and developed in critical areas of engineering practice. They are used, in particular, in aircraft, rocket and automotive engineering, shipbuilding, railway transport, agricultural machinery production and construction. Advantages of these materials are high strength and stiffness, lightness, high fatigue strength, chemical inertness, heat and electrical conductivity, and others.

Because these materials are used in critical areas of engineering practice, so this makes their long-term aging and creep characteristics of paramount importance. At the same time, the physical and chemical characteristics of these materials essentially changed after long-term operation, significantly due to the aging process [1-4]. Thus, investigations of aging of these materials are much needed.

Experimental studies on alternation of natural and thermal aging and deformation aging were conducted to study the evolution of creep characteristics of carbon fiber reinforced plastics (CFRP). Specimens made of CFRP of the T26/22502/I131636 brand with a working length of 140 mm, a width of 15 mm and a thickness of 0.75-0.85 mm we investigated. The experimental creep curves after different aging programs were received.

The first series of specimens were tested on alternation of creep, natural and thermal aging and cyclic loadings. In total experiments were carried out during 4 years. At the first stages of deformation aging a hardening effect during creep by 1.5 times is occurred. Then, after additional aging the softening is observed (the creep deformation was only 1.35 times

higher than deformation without aging). After 4 years of aging, the creep deformation was equal to only 0.92 from initial deformation without aging. Therefore, the process of aging has non-monotonic character, which should be taken into account in engineering practice at design of structural elements made of polymer composite materials.
The second series of specimens were tested only on alternation of natural and thermal aging at negative temperatures. In total experiments were carried out during 4 years. Then specimens were tested on creep. It is shown, that such aging program has no effect on creep characteristics and creep deformation in this case is equal to initial deformation without aging.

References
[1] Struik L.C.E. Physical aging in amorphous polymers and other materials. Amsterdam, Oxford, New York: Elsevier Sci. Publ. Comp. 1978. 229p.
[2] Nadai A. Theory of flow and fracture of solids. McGraw-Hill. New York. 1963. Vol. 2. 321p.
[3] Hutchinson J.M. Physical aging of polymers // Progress in polymer science. 1995. Vol. 20(4). P. 703-760.
[4] Arutyunyan R.A. The problem of strain aging and long-term fracture in mechanics of materials. SPb.: Publishing House of the St. Petersburg State University. 2004. 252p. (in Russian).

EVOLUTION OF THE MICROSTRUCTURE OF OBSTACLES FROM FCC ALLOYS UNDER HIGH-VELOCITY IMPACT CONDITIONS

Atroshenko S.[1,2], Smakovsky M.S.[3], Savenkov G.G.[4,5]
1 - Institute for Problems in Mechanical Engineering, Russian Academy of Sciences, St. Petersburg
2 - Saint Petersburg State University, Saint Petersburg, Russia
3 - Machine-building plant "Armalit", St. Petersburg, Russia
4 - Saint Petersburg State Technological Institute (Technical University), Saint Petersburg, Russia
5 - Physico-Technical Institute named after A.F. Ioffe RAS, St. Petersburg, Russia
satroshe@mail.ru

Protection of various modern technical objects experiencing high-energy loads from the impact of irregularly shaped strikers (for example, ammunition fragments, micrometeorites, etc.) with impact velocities over 1.5 - 2.0 km/s is of significant scientific and practical interest. Computer simulation of the processes of high-speed interaction of strikers with various objects in order to create optimal structures requires deep knowledge of the physical and mechanical properties and processes occurring in the thickness, at least of the material of the target (object). However, the existing technical measuring instruments make it possible to register only the kinematic parameters of deformation and destruction of the obstacle and the striker, while the development of internal processes remains inaccessible for visualization. In addition, the physical processes of high-speed deformation and fracture occurring in obstacles are highly dependent on the set of contact boundaries that are inherent in irregularly shaped strikers, and in computer modeling and experimental studies, strikers, as a rule, have the correct geometric shape (cylinder, sphere). As a result, there is a significant loss in the accuracy of calculations.
Therefore, the study of the evolution of the microstructure of the target material under the conditions of a high-speed impact with an irregularly shaped striker comes to the fore, despite the fact that such studies are of a post-factor nature and the state of the microstructure at the moment of dynamic action may differ from that after dynamic loading. But it can be noted that it is the processes of restructuring the internal structure of the material during its dynamic deformation and destruction that determine the physical and mechanical properties of the medium.
In this work, we investigated the microstructure of samples cut from targets made of an aluminum alloy of the AMg6 type (but additionally alloyed with scandium), aluminum bronze, and stainless steel 18Cr-10Ni-Ti, pierced by compact irregularly shaped impactors (otherwise called impact "nuclei" [1, 2]). The initial velocity of impact of the striker with the obstacle was ~ 1.8 - 2.0 km/s.
References
1. Physics of the explosion. T.2. / Ed. L.P. Orlenko. M.: FIZMATLIT, 2002. 656 p.
2. Kolpakov V.I., Savenkov G.G., Rudomyotkin K.A., Grigoriev A.Yu. Mathematical modeling of the formation of compact projectiles from low-spherical linings // Technical Physics. 2016.Vol. 86. N8, pp. 21 - 25.

UNIVERSAL MODELING METHOD IN THE DIFFERENTIAL AND INTEGRAL EQUATIONS OF CONTINUOUS MEDIA

Babeshko V.A., Evdokimova O.V.
Kuban State University, Krasnodar, Russia
babeshko41@mail.ru

In the works of the authors it is established that packed block elements describing solutions of boundary value problems for differential equations
continuum mechanics, physics, including quantum physics, as well as in a number of related fields, are fractals, that is, self-similar elements in these spheres [1-3]. Since fragments of differential equations are present in a number of integral

equations of mixed boundary value problems, including the Wiener-Hopf type, fractals are also found in them. The concept of fractals was introduced by the American mathematician Benoit Mandelbrot. Self-similarity means the possibility of exhausting the basic properties of objects or processes by one or another set of fractals. For example, in quantum mechanics, a fractal is a Schrodinger equation describing the properties of any elementary particle. The study of boundary value problems for differential equations of mechanics and physics of real natural or technological processes, linear or nonlinear, turned out to be possible in the vast majority of cases to describe fractals generated by Helmholtz equations, analogues of Schrodinger equations, but in the macrocosm. Probably, there is a reason for this, which follows from theoretical physics that "quantum mechanics contains classical mechanics as a limiting case" (Landau L.D., Lifshits E.M. Quantum Mechanics. Tom. 3. M.: Fizmatlit. 2001, p. 37). Having taken this position, the authors have built a fairly general universal modeling method consisting in the search for fractals in various processes. Along this way, it has already been possible to investigate a number of problems that previously could not be solved, either by analytical or numerical methods. In the lecture:

1. The application of the universal modeling method in boundary value problems for systems of partial differential equations is described.

The construction of fractals -packed block elements is described.

Methods of their application are given to represent decompositions of solutions of boundary value problems for systems of partial differential equations by fractals - solutions of boundary value problems for individual partial differential equations.

2. The application of the universal modeling method in boundary value problems for systems of Wiener-Hopf integral equations is described

The construction of fractals -packed block elements is described.

Methods of applying them to represent decompositions of solutions for systems of integral equations by fractals – solutions for individual integral equations are given.

3. The applications of these approaches to problems for cracks of a new type and contact problems with a deformable stamp are considered.

The work is supported by the Russian Science Foundation, project No. 22-21-00128.

References

1. Babeshko V.A., Evdokimova O.V., Babeshko O.M Fractal Properties of Block Elements and a new Universal Modeling Method// Doklady Physics 2021, Vol. 66, No. 8, pp. 218–222. DOI: 10.1134/S1028335821080012

2. Babeshko V.A., Evdokimova O.V., Babeshko O.M Block Elements in Boundary-Value Problems for Sets of Differential Equations of Mechanics and Physics in Non-Classical Domains // Doklady Physics 2021, Vol. 66, No. 6, pp. 169-174. DOI: 10.1134/S102833582106001X

3. Babeshko V.A., Evdokimova O.V., Babeshko O.M. On a Method for Solving Boundary Value Problems of the Dynamical Theory of Elasticity in a Quarter Plane//Mechanics of Solids, 2021, Vol. 56, No. 7, pp. 217–222. DOI: 10.3103/S0025654421070037

NATURAL OSCILLATIONS OF THE LIQUID COLUMN IN AN OIL WELL IN THE PRESENCE OF A FRACTURED HYDRAULIC FRACTURING

Bashmakov R.A.[1,2], Shagapov V.Sh.[2]
1 - Bashkir State University, Ufa, Russia
2 - Mavlutov Institute of Mechanics, Ufa Federal Research Center RAS, Ufa, Russia
bashmakov_rustem@mail.ru

We consider natural oscillations of liquid column in an oil well, arising at sudden closing or opening of well pumps (water hammer). The period of oscillations, the intensity of oscillations damping is determined by the length of the liquid column, its rheological properties, as well as reservoir characteristics of the bottomhole formation zone (in particular, permeability coefficients, quality of well perforation and properties of fractures formed). Based on mathematical model describing motion of liquid column in the well, when its upper end is open, and filtration in the bottomhole zone subjected to hydraulic fracturing, solutions to the problem of natural damped oscillations of the liquid column in the well have been obtained. Dependences of frequency and damping coefficient of pressure oscillations at different sections of the well on the values of formation permeability and parameters of hydraulic fracturing have been studied. It is shown, that acoustic diagnostics based on the analysis of natural oscillations in the well can serve as an effective tool for diagnostics of bottomhole formation zone.

This work was supported by the Russian Science Foundation (Grant No. 21-11-00207, https://rscf.ru/project/21-11-00207/).

EFFECT OF GRAPHENE PULL-OUT FROM CERAMIC MATRIX ON CRACK GROWTH RESISTANCE OF CERAMIC/GRAPHENE COMPOSITES

Bobylev S.V.[1,2]
1 - Institute for Problems in Mechanical Engineering of the Russian Academy of Sciences, St. Petersburg, Russia
2 - Peter the Great St. Petersburg Polytechnic University, St. Petersburg, Russia
bobylev.s@gmail.com

A theoretical model is proposed that describes the effect of graphene platelets pull-out from ceramic matrix on the crack growth resistance of ceramic/graphene composites. We consider mode I crack propagating perpendicularly to the system of parallel graphene plates whose pull-out from ceramic matrix in the crack bridging zone behind crack tip hampers crack opening. The dependences of fracture toughness on the content of graphene and the sizes of graphene platelets are calculated in the exemplary case of a stabilized zirconium oxide (YSZ)/graphene composite. We demonstrated that fracture toughness increase depends on volume fracture c of graphene as $\sim c^{0.8}$. If graphene platelets pull-out is the dominating mechanism controlling crack propagation in ceramic/graphene composite then fracture toughness can increase by up to ~100% depending on graphene concentration and platelets dimensions, while typically observed in experiments fracture toughness increase is about 20–60%. Calculations predict that the maximum crack growth resistance is achieved in the case of long and thin graphene platelets, provided that the latter have sufficient strength and adhesion to the matrix. The model shows a good correlation with experimental data at low graphene concentrations.

WAVES OF SHOCK COMPRESSION AND ISENTROPIC EXPANSION IN REFRACTORY METALS NEAR THE REGION OF THE LIQUID–VAPOR PHASE TRANSITION

Boyarskikh K.A.[1,2,3], Khishchenko K.V.[1,2,3,4]
1 - Joint Institute for High Temperatures RAS, Moscow, Russia
2 - Moscow Institute of Physics and Technology, Dolgoprudny, Russia
3 - Institute of Problems of Chemical Physics RAS, Chernogolovka, Russia
4 - South Ural State University, Chelyabinsk, Russia
shagom55@gmail.com

In this work, we calculated the characteristics of waves of shock compression and isentropic expansion in refractory metals (Ti, Mo, Re) near the region of the liquid–vapor phase transition at high temperatures and pressures. The calculations were carried out using three equations of state, the first of which is the van der Waals equation. The second is the equation of state obtained by considering the model problem of charged hard spheres. The third equation is the equation of state for interacting point centers. The first two equations contain two parameters each, and the third equation contains three parameters. Simple models allow fast and simple calculations. To determine the parameters of the models of equations of state for specific substances, three approaches were applied. The first approach is based on the Cailletet–Mathias rectilinear diameter rule. The second approach is based on the calculation of the transition energy from the condensed phase to the gas. The third approach consists in varying the parameters of the equations of state in a wide range and minimizing deviations from experimental data on the isobaric expansion of metal melts. The third approach should be recognized as the best method of evaluation, for the implementation of which the smallest number of assumptions was used. In addition, the third approach makes it possible to obtain the best agreement with the experimental data. The shock adiabats and isentropes of unloading of shock-compressed metals with an initial state near the region of the liquid–vapor phase transition are calculated. This work is done under the support from the Russian Science Foundation (grant No. 19-19-00713, https://rscf.ru/project/19-19-00713/).

NUMERICAL SIMULATION OF HIGH-TEMPERATURE SUBSONIC AIR AND NITROGEN FLOWS IN A HIGH-POWER RF-PLASMATRON

Bryzgalov A.I.
Ishlinsky Institute for Problems in Mechanics RAS, Moscow, Russia
bryzgalov@ipmnet.ru

An efficient method for thermal protection material testing is to subject a specimen to a high-enthalpy gas flow generated in a powerful RF-plasmatron. Two such plasmatrons, IPG-3 and IPG-4, are operated at IPMech RAS for a wide range of conditions relevant to aerospace applications. To complement the experiments, a computer program IPG2D was developed in FORTRAN-90, providing the capability to simulate axisymmetric non-equilibrium plasma flows in the test chamber, to obtain the temperature and concentration fields and calculate the heat fluxes onto the surfaces with different catalytic activity. This program enhances the capabilities of existing software tools where equilibrium plasma flows are calculated in the test chamber, and non-equilibrium effects are only taken into account along the stagnation line in the boundary layer, in order to obtain the effective recombination probability for the tested material. In this work, two sets of recent experiments performed in IPG-4 facility are analyzed by IPG2D code,

including 28 tests for dissociated air, and 12 tests with nitrogen plasma. All experiments were carried out with water-cooled models having a flow calorimeter for the heat flux determination; the experiments differ by the test chamber pressure and power input to plasma. Accordingly, the simulations were carried out for the experimental conditions, with the effective recombination probabilities obtained in the literature. In the simulations, the heat flux distributions over the surface of the test model were obtained. The non-uniformity of the heat flux was evaluated by comparing the maximum and average heat fluxes. IPG2D code validation was performed by comparison of the heat fluxes with the measured ones. It is shown that the heat flux non-uniformity is within 5%, the discrepancy between the experimental data for air plasma is within 10%, while for nitrogen plasma it is within 15% (although the maximum error obtained in one case is 29%). The results obtained confirm the validity of the approach adopted in IPMech RAS for the calculation of effective recombination probabilities, as well as validate the IPG2D code for calculation of heat fluxes on water-cooled surfaces.

OSCILLATIONS EXCITED IN INTERACTING FITZHUGH-NAGUMO NEURONS DUE TO THE DELAY IN THE COUPLING

Bukh A.V., Elizarov E.M., Shepelev I.A., Strelkova G.I.
Saratov State University, Saratov, Russia
buh.andrey@yandex.ru

We study the excitation of oscillations in the system of coupled FitzHugh-Nagumo neurons. Each neuron is initially set to an excitable regime. An increase in parameter of the single oscillator γ leads to an expansion of the region of oscillatory regime existence. This is connected with an approach to the oscillatory regime area in the single neuron with an increase in γ. The oscillation frequencies depend only on the time delay. The oscillation regions are depicted using Lyapunov exponents for cases of two coupled FitzHugh-Nagumo neurons and a ring of locally coupled FitzHugh-Nagumo neurons. In addition, the number of excited neurons in the ring is depicted on the (τ,σ) parameter plane, where we show that the increase in time delay leads to the excitaion of oscillations in the system, and for the larger values of time delay parameter neurons begin oscillate at smaller values of sigma. Herewith we study the effect of coupling range in the ring of interacting FitzHugh-Nagumo neurons with time-delayed coupling.

STRAIN INDUCED PRISMATIC DISLOCATION LOOP CLOSE TO THE HETEROINTERFACE IN THE HYBRID AXIAL NANOWIRE

Kolesnikova A.L.[1,2], Gutkin M.Yu.[1,2], Chernakov A.P.[2,3], Romanov A.E.[2,3]
1 - Institute for Problems in Mechanical Engineering, Russian Academy of Sciences, St. Petersburg, Russia
2 - ITMO University, St. Petersburg, Russia
3 - Ioffe Physical Technical Institute, Russian Academy of Sciences, St. Petersburg, Russia
anton.chernakov@gmail.com

The possibility of forming a strain-induced prismatic dislocation loop (PDL) in a two-phase hybrid nanowire with a transverse heterointerface, an axial nanowire (ANW), has been theoretically studied. It has been found that due to the stresses caused by the contact of two crystalline materials with different lattices, at certain ratios of the ANW and PDL radii, at certain distances between the PDL and the interface, and at certain misfit parameters between the crystal lattices of the ANW parts, there is an energy possibility for the formation of PDLs localized near the heterointerface. It is shown that for each ANW radius there is a critical misfit parameter, below which the formation of a PDL is energetically unfavorable, and vice versa, for a given misfit parameter, in ANW with a radius smaller than the critical value, the PDL formation is energetically impossible. The dependence of critical nanowire radius on the misfit parameter has been depicted and its approximate function has been found.

REORIENTATION OF A RIGID BODY BY MEANS OF AUXILIARY MOVABLE MASSES

Chernousko F.L.
Ishlinsky Institute for Problems in Mechanics RAS, Moscow, Russia
chern@ipmnet.ru

Mobile robots controlled by auxiliary internal movable masses called capsule robots, or vibro-robots, are used for inspection and monitoring in technology and medicine.
To implement 2D and 3D movements of these robots, their internal masses should perform certain motions relative to the body. Algorithms for the body reorientation based on the motions of internal masses are discussed. These algorirhms can be of interest also for the orientation control of spaceship and other vehicles.

THE INFLUENCE OF THE GRAVITY OVERRIDE ON OPTIMAL WATER-ALTERNATING-GAS STRATEGIES

Chernova A.A.
Institute of Mechanics, Lomonosov Moscow State University, Moscow, Russia
anya_chernova_2504@mail.ru

We investigate the optimal water-alternating-gas (WAG) injections into petroleum reservoirs. When water and CO_2 are injected to displace oil, then the less denser gas rises to the roof of the reservoir, whereas the denser water phase sinks to the base of the reservoir. Thus, some oil can be bypassed by the injected fluids causing reduction in the WAG efficiency. The gravity override also influences the optimal completion intervals of the injection and producing wells. For example, if injection well is completed only at the roof of the reservoir, then CO_2 flows to the producing well along the roof and the sweep efficiency is lower.
To determine the most profitable strategy of WAG, we couple a 2-D cross-section reservoir model with a simple economic model of WAG and aim at the net present value (NPV) maximization [1,2]. At the initial moment of time the reservoir $0 \le X \le L$, $0 \le Z \le H$ is saturated with oil at connate water saturation, where X and Z are the horizontal and vertical coordinates. The oil displacement is simulated by placing two point sources at X=0 (Injector) and X=L (Producer), which are opened at t=0. We consider various depths for the Injector and Producer. Either of the point sources can be located near the upper boundary Z=0 (i.e. near the roof of the reservoir), at Z=H/2 and Z=H (i.e. at the base of the reservoir). The Injector is operated at a constant volume injection rate at reservoir conditions for any displacing fluid. The Producer is operated at a constant bottom-hole pressure that is equal to the initial reservoir pressure. We consider only two types of displacing fluid, namely water and CO_2. Both continuous and alternating injection scenarios are examined. The water and hydrocarbon (HC) mixture flow is simulated by a system of the mass conservation equations for each component of the HC mixture and water and Darcy`s law.
We propose two dimensionless similarity parameters characterizing the influence of the gravity override on the WAG efficiency [3]. The first parameter characterizes the reservoir anisotropy and associated pressure distribution. The second parameter characterizes the influence of the gravity. We investigate the optimal gas flooding strategies in the space of these parameters and present the maps showing the optimal strategy and NPV against the dimensionless parameters. Also, we investigate the influence of the Injector and Producer completion intervals on optimal WAG scenario. For a fixed dimensionless parameters and injection strategy, we present a map showing optimal completion intervals for both Injector and Producer.
The authors acknowledge funding from the Russian Science Foundation under grant # 19-71-10051.
[1] Afanasyev A., Andreeva A., Chernova A. Influence of oil field production life on optimal CO_2 flooding strategies: Insight from the microscopic displacement efficiency // Journal of Petroleum Science and Engineering. 2021. V. 205. P. 108803
[2] Afanasyev A., Andreeva A., Chernova A. Numerical optimisation of CO_2 flooding using a hierarchy of reservoir models // Advances in Geosciences. 2021. V. 56. P. 19-31
[3] Chernova A., Afanasyev A. Influence of the gravity override on optimal gas flooding strategies // Fluid Dynamics. 2022. To appear.

TSALLIS DIVERGENCES IN THE STATISTICAL LINEARIZATION OF DYNAMIC SYSTEMS

Chernyshov K.R.
V.A. Trapeznikov Institute of Control Sciences, Moscow, Russia
may18.2005@gmail.com

Statistical linearization techniques have taken an appreciable place among approaches concerned with solving different problems related to investigation of mechanical systems; and papers [1-3] and others may serve as an evident confirmation. The present paper proposes an approach to the statistical linearization of dynamic systems, based on Tsallis divergence [4] as a measure of stochastic dependence.
The statistical linearization of input/output system mappings is just a non-linear problem, whose solution is considerably determined by a dependence characteristics of input and output processes of a system under study. Existing approaches are based on the conventional linear correlation, what may lead to construction models, where the output variable will be identically equal to zero. In particular, such a possibility is shown in the present paper, in which an approach is proposed aimed to remove conventional correlation technique drawbacks. To exclude these, more complex, non-linear, measures of dependence are applied. A particular place is taken by consistent ones, what means vanishing if and only if the random values are stochastically independent.
In the paper, information-theoretic approach a problem statement is considered concerned with the statistical linearization of multi-input/multi-output discrete time dynamic systems. Such an approach is based on applying quadratic Tsallis divergence under construction a statistical linearization criterion. When one of the two densities is the joint probability distribution density of the random values (vectors), while the second one is the product of their marginal densities, a corresponding divergence becomes a measure of dependence that is natural to be referred as quadratic Tsallis mutual information.

Computationally, especially under calculations by the use of sample dada, Tsallis divergence is more attractive than Kullback-Leibler one, since the latter involves the "integral of logarithm", what is commonly recognized as more complex in the comparison with Tsallis divergence, where the logarithm is absent at all.

In the paper, the statistical linearization criterion is the condition of coincidence of the mathematical expectations of the output processes of the system and model; and the condition of the coincidence of quadratic Tsallis mutual information of input and output processes of the system and quadratic Tsallis mutual information of the input and output processes of the model. Expressions to determine matrix-valued weight function coefficients of the linearized model are obtained. Meanwhile, the expressions obtained are based on quadratic Tsallis mutual information and define a measure of stochastic dependence being consistent in the Rényi sense: meeting axioms [5].

1. Cai G.Q., Suzuki Y. On statistical quasi-linearization // Int. J. Non-Linear Mechanics. 2005. Vol. 40, No. 8, P. 1139-1147.
2. Spanos P.D., Kougioumtzoglou I.A. Harmonic wavelets based statistical linearization for response evolutionary power spectrum determination // Prob. Eng. Mech. 2012. Vol. 27, No. 1. P. 57-68.
3. Changda Feng, Xinzhong Chen. Inelastic responses of wind-excited tall buildings: Improved estimation and understanding by statistical linearization approaches // Eng. Structures. 2018. Vol. 159. P. 141-154.
4. Tsallis C. Introduction to Nonextensive Statistical Mechanics. Approaching a Complex World. Springer, 2009.
5. Rényi A. On measures of dependence // Acta Math. Hung. 1959. Vol. 10, No. 3-4. P. 441-451.

MOLECULAR DYNAMICS STUDY OF THE MECHANICAL PROPERTIES OF MULTICOMPONENT TI-BASED COATINGS ON A TI SUBSTRATE

Dmitriev A.I., Nikonov A.Yu., Shugurov A.R.
Institute of Strength Physics and Materials Science of Siberian Branch Russian Academy of Sciences, 2/4, pr. Akademicheskii, 634055 Tomsk, Russia
dmitr@ispms.ru

Ceramic-based coatings with high hardness, oxidation resistance, and thermal stability are increasingly used to improve wear and corrosion resistance of parts and mechanisms in the manufacturing, automotive, aerospace, shipbuilding and other industries. However, alonge with the high hardness of ceramic coatings is often accompanied by their low crack resistance. To develop methods to increase the crack resistance of ceramic-based coatings, detailed investigations into the mechanisms of cracks initiation and the patterns of their propagation in the coating-substrate system are required. The use of computer simulation methods on various scales opened up wide opportunities for study the deformation and fracture development of multicomponent systems. This paper presents the results of experimental and theoretical studies of the destruction of Ti-Al-N ceramic coatings deposited on the compliable metal substrate under uniaxial tension. With use of molecular dynamics simulation and subsequent experimental validation the fracture patterns of $Ti_{0.45}Al_{0.55}N$ coatings on a initially defect-free titanium substrate were studied. As a result of the studies carried out, the influence of the inhomogeneous distribution of aluminum in coatings on the nature of nucleation and propagation of cracks in them at the atomic level was revealed. It is shown that cracks in the $Ti_{0.45}Al_{0.55}N$ coating propagate mainly in areas with low Al content. In this case, after the formation of the first cracks due to the presence of a rigid bond between the coating and the substrate, the stretching of the latter causes further loading of the coating, leading to its multiple cracking. The staged nature of the destruction of $Ti_{0.45}Al_{0.55}N$ coatings is revealed, which is due to the successive development and competition between different mechanisms of stress relaxation. The influence of the thickness of coatings on the nature of the development of competing mechanisms of their deformation and destruction was demonstrated. The simulation results agree qualitatively well with experimental observations.

This study was funded by the Russian Science Foundation, grant No. 22-19-00441, https://rscf.ru/project/22-19-00441.

MECHANICS AND NONLINEAR DYNAMICS OF GRAPHENE NANORIBBONS ON A SUBSTRATE

Savin A.V.[1], Korznikova E.A.[2,3], Dmitriev S.V.[3]
1 - N.N. Semenov Federal Research Center for Chemical Physics
2 - Ufa State Aviation Technical University
3 - Ufa Federal Research Centre of the Russian Academy of Sciences
elena.a.korznikova@gmail.com

Graphene has attracted considerable interest over the past two decades due to its exceptional conductivity, mechanical strength, heat resistance, etc. Large-scale graphene production is usually associated with growth on substrates, and the effects of mutual interaction of graphene with the substrate surface are of particular importance. In some cases, the stable connection of the two surfaces may be lost, which leads to an unpredictable change in the properties of the material and its mechanical behavior. In this paper, we consider several types of surface instabilities of graphene nanoribbons, their dynamics and influence on mechanical properties. One of the studied objects, which should be mentioned, is a ripplocation - an atomic scale defect of the folded type surface [1]. Surface and volume instabilities in layered nanomaterials have recently attracted the attention of researchers because they have the properties of topological solitons that are able to efficiently transfer mass and energy and mediate plastic deformation. In this study, the dynamics of graphene scrolls, ripplocations and several other perturbations on a graphite substrate is analyzed using full-atomic molecular dynamics and using a two-dimensional chain model. It is shown that such objects are stable solitary waves that propagate with practically no energy radiation [2]. Our results contribute to understanding the behavior of nanofibers of a two-dimensional material on a substrate.

The work of KEA was supported by the Council for Grants of the President of the Russian Federation for state support of Young Russian scientists and for state support of leading scientific schools of the Russian Federation , grant number NSH-4320.2022.1

References

1. Barsoum MW, Tucker GJ. 2017 Deformation of layered solids: Ripplocations not basal dislocations. Scripta Materialia 139, 166–172. (doi:10.1016/j.scriptamat.2017.04.002)

2. Savin AV, Korznikova EA, Dmitriev SV. 2020 Twistons in graphene nanoribbons on a substrate. Physical Review B 102. (doi:10.1103/PhysRevB.102.245432)

INFLUENCE OF SPHERICAL STRESS STATE ON THE WAVE PROPERTIES FOR REDUCED KELVIN'S MEDIUM

Drepin M.A.
Peter the Great St. Petersburg Polytechnic University, St. Petersburg, Russia
mihail.drepin@gmail.com

We consider the influence of spherical stress state on the wave propagation in the reduced Kelvin's medium, stability analysis. In this work

* We have obtained constitutive relations for the reduced Kelvin's medium in prestressed state;

* We have obtained and analysed dispersion relations for special cases of wave propagation for reduced Kelvin's medium in the vicinity of a prestressed state; we have shown new ways of loss of stability.

We obtained that spherical stress state leads to generating new types of instability. Have shown the influence on the stability of longitudinal waves of the elastic constant alpha, creating a leveling effect with respect to instability under compression. Also, the material changes its behavior with respect to shear waves in tension. The special point is the stretching twice. Under such stretching, the effective constant alpha becomes equal to zero and the dispersion curve becomes a straight line.

INTERDIFFUSION MODELS FOR VISCOELASTIC MEDIA

Dudin D.S.[1,2], Keller I.E.[1,2]
1 - Institute of Continuous Media Mechanics UB RAS
2 - Perm National Research Polytechnic University
dmitryovj@yandex.ru

Coupled mechanodiffusion processes accompany strengthening at implantation of nitrogen atoms in the surface layer by ion-plasma technologies, forming of corrosion film on metallic alloys in an aggressive environment, and they are involved in microstructure formation of metallic materials under the severe plastic deformation, improving the strength properties significantly.

The coupled systems of the equilibrium and substance balance equations for multicomponent viscoelastic media, which are written in different reference systems, are analyzed. The mixture theory under the classical thermodynamics of irreversible processes is used to formulate the mechanodiffusion model. The thermodynamic inequality is satisfied using the linear phenomenological equations, establishing the couple between diffusion and mechanical processes. The approaches are discussed to be applied for separating diffusion of particles from matter deformation movement, in particular when material undergoes the deformations being independent of the interdiffusion. The reference frames are splitted into three groups. In the Kirkendall frames the interdiffusion is only permitted that allows for treatment of the marker experiment. The Fick frames are defined by the reference velocities being superposition of the particle velocities with the weigh factors. Third reference frame utilize the velocity of marker, which in a real experiment does not interact with the investigated material through diffusive path, and therefore it represents the material velocity. Within the group different composition variables are used for describing diffusion. It is shown that the diffusion coefficients in the various frames are dependent. The mechanodiffusion models are formulated both with and without the incompressibility condition.

MULTIAXIAL FATIGUE DAMAGE MODEL FOR FIBER-REINFORCED COMPOSITES

Elkin A.S., Gaibel V.A., Sergeichev I.V.
Skoltech
aleksandr.elkin@skoltech.ru

In polymer composite materials, non-uniform degradation of stiffness and strength has to be considered. Multilayered fiber-reinforced plastics have anisotropic nature, and even a simple loading causes a complex stress-strain state. Thus, to predict the fatigue performance of composites, we propose a mathematical model that considers the multiaxial stress state. The main purpose of the model is to predict the damage initiation, the influence of on-axis and off-axis loadings on stiffness and strength degradation. We developed and implemented the fatigue model as a subroutine in the ABAQUS finite element software. The model was identified and verified using previously published S-N curves and constant life diagrams. The compliance between the proposed material model, and the published results confirmed the hypothesis that stiffness degradation occurs because of accumulation of micro-cracks in a matrix and fiber breakage, that significantly reduce the maximum compressive load capacity. In addition, the model showed that additional off-axis loading substantively speeds up the fatigue of composites. Overall, the model accurately predicts the fatigue capacity of fiber-reinforced composites.

LINEAR AND NONLINEAR PLANE LONGITUDINAL WAVES IN THE ENVIRONMENT OF SLEPUAN-PALMOV

Korsakov M., Leonteva A., Malkhanov A., Erofeev V.
MERI RAS, Nizhny Novgorod, Russia
erof.vi@yandex.ru

In the mechanics of generalized continua, in addition to models of media with internal rotational degrees of freedom (Cosserat continuum) and gradient models (continua of Le Roux, Jaramillo, Tupin, etc.), there are known models of media with oscillatory degrees of freedom. Their appearance is associated, first of all, with the works of L.I. Slepyan (one-dimensional system) and V.A. Palmov (three-dimensional system).

The Slepyan - Palmov model is a linear elastic carrier medium and noninteracting oscillators (elastic or viscoelastic) suspended at each point. When formulating this model, it is postulated that the dynamic behavior of the carrier medium is described by the Lamé equations, and the natural frequencies of the oscillators associated with it are continuously distributed.

Even with a low damping of the oscillators, the spatial damping of vibrations in such a medium turns out to be finite. This model is effectively used in calculating the vibration of aircraft, objects of rocket and space technology and the submarine fleet.

The dispersion properties of the system are investigated. It is shown that wave propagation is characterized by two dispersion branches ("acoustic" and "optical"). Dispersion is absent in the low-frequency branch at low frequencies and at high frequencies in the high-frequency branch. The waves described by each of the two dispersion branches propagate in their own frequency range, which do not intersect. There is a frequency non-transmission region. In the entire range of frequencies and wavenumbers, the phase velocity curves lie above the corresponding group velocity curves (normal dispersion).

The one-dimensional version of the system under consideration is generalized by introducing into it a nonlinearity associated with the nonlinearity of the carrier medium. It is shown that a nonlinear stationary elastic wave can form in a medium with internal oscillatory degrees of freedom. Such a wave is periodic and moves faster than waves in a linear medium. The wave has a sawtooth shape, the wavelength increases with increasing amplitude.

PECULIARITIES OF ELASTIC GUIDED WAVE PROPAGATION IN FIBER-REINFORCED COMPOSITE LAMINATES INDUCED BY THEIR COMPLEX MICROSTRUCTURE

Evdokimov A.A., Eremin A.A.
Kuban State University, Institute for Mathematics Mechanics and Informatics, Krasnodar, Russia
evdokimovmail27@gmail.com

Elastic guided waves are widely applied in the non-destructive evaluation and structural health monitoring for inspection of laminate thin-walled composite structures since they are sensitive to defects of various nature, such as delaminations, cracks, corrosion damage, etc. In many aspects, the accuracy of damage detection and identification depends on the reliability of the mathematical and computer models of wave propagation and diffraction. Quite a lot of efficient models are being proposed for isotropic materials which allow achieving the required accuracy compared to experimental results. However, additional difficulties may occur in the case of fiber-reinforced laminate composites due to complex internal structure of these materials. For instance, in carbon fiber-reinforced plastic plates, non-homogeneous distribution of fibers with local densifications of either matrix of fibers could result in local changes of density and elastic constants. Since the size of such densifications might be comparable to ply thickness, they act as

obstacles for propagating guided waves. This results in the appearance of continuously scattered and converted wavefields observed after the incident wavepackage (B. Hennings, et.al., Composite Structures, 2016, 151) and thus could affect frequency-amplitude characteristics and dispersion properties of propagating guide waves.
To model elastodynamic behavior of complex composite structures, it is convenient to use the finite element method (FEM) implemented in commercial software. The FEM models are flexible with respect to the size, shape, and material properties of the inspected waveguide structure. However, the simulation of wave processes in elongated waveguide structures is often associated with high computational costs and additional post-processing to distinguish waves of different types. Moreover, with infinite waveguides, it is necessary to restrict the area with artificial boundary conditions, which simulates outflow of wave energy to infinity. To overcome these difficulties, the hybrid FEM-analytic approach (E. Glushkov, et.al., Acoust. Phys., 2018, 64(1)) is adopted in this study. Its main idea is to couple a mesh-based FE approximation in a local area containing the source and obstacles with an explicit guided wave representation in the infinite outer domain.
To simulate local structural inhomogeneities and to study their influence on the amplitude-frequency characteristics and dispersion properties of the excited waves, the ply density and elastic constants in an elongated part of the infinite waveguide are supposed to be stochastically distributed quantities (E. Zimmermann, et. al., GAMM - Mitteilungen. 2018, 41). For the quantitative assessment, several numerical characteristics such as the ratio of conversion and attenuation are introduced and analyzed for composites with unidirectional and cross-ply stacking sequencies. The obtained theoretical results are also qualitatively compared to the available experimental data.

ANISOTROPY OF MECHANICAL PROPERTIES OF ADDITIVELY MANUFACTURED STAINLESS STEEL 316L IN DIFFERENT LOADING CONDITIONS

Fedorenko A.N.[1], Fedulov B.N.[2], Kuzminova Yu.O.[1], Evlashin S.A.[1], Staroverov O.A.[3], Lomakin E.V.[2]
1 - Center for Material Technologies, Skolkovo Institute of Science and Technology
2 - Department of Mechanics and Mathematics, Lomonosov Moscow State University
3 - Center of Experimental Mechanics of Perm National Research Polytechnic University
a.fedorenko@skoltech.ru

In the presented study the anisotropy of mechanical properties and sensitivity to loading conditions are characterized for stainless steel 316L, fabricated via laser powder bed fusion (LPBF). Experimental set for mechanical testing includes LPBF samples for tension, compression and shear, which were built in three different mutually orthogonal directions. Test results show a dependency of mechanical characteristics to the build direction in some cases, while no significant differences in other ones. In particular, tensile sample built vertically has lower yield and ultimate stress in comparison with horizontally oriented. Moreover, numerical simulation of build process revealed high residual stresses in specimens, and the stress level depends on orientation. Virtual tensile test was also performed with the presence of predicted residual stresses. Simulation show, that Young’s modulus, measured in the sample with presence of residual stresses, is reduced to about 25% in comparison with conventional value of 190-200GPa at room temperature. Physical tensile test of considered steel samples also shows similar difference in Young’s modulus. Therefore, the residual stress is a potential explanation of the apparent anisotropy, and it should be considered together with other factors of anisotropy, such as porosity and microstructure. The proposed experimental setup gives data to develop anisotropic elastoplastic model and failure criteria, which are also discussed in the presented study.
This research was supported by the Russian Science Foundation (Grant No. 20-11-20230).

EFFECTIVE CHRONO-PHYSICAL-MATHEMATICAL MODELING OF DETERMINING FUNCTIONAL PROPERTIES HOMOGENEOUS AND HETEROGENEOUS RHEOLOGICALLY SIMPLE AND COMPLEX MEDIA. RAPID TESTS FOR PREDICTION OF LONG-TERM PROPERTIES

Fedorovskiy G.D.
Saint-Petersburg University, Russia
g.fedorovsky@spbu.ru

Currently, there is a rapid development of the experimental and theoretical comprehensive study of the determining functional properties of various isotropic and anisotropic homogeneous and heterogeneous rheologically simple and complex media in the field of quasi-static and dynamic monotonic and non-monotonic influences. The objectives of the research are to solve non-trivial problems of establishing relationships between physical, mechanical and other properties in the linear and non-linear region, including identification of the dependence of these properties on the parameters of the material structure, manufacturing technologies and impacts during operation, effective prediction of properties in a wide range of parameter changes [1, etc.]. The study of the relationship with each other of the following characteristics of materials: coefficients of thermal linear and volume expansion, thermal conductivity of heat capacity, temperature, density, moduli of elasticity and compliance, yield strength and strength, coefficients of friction, electrical resistance, magnetic permeability, optical refractive indices, laboratory and transformed time according to various mechano-physical-chemical correspondences, horizontal and vertical correspondence scales and other linear and non-linear properties of materials, hysteresis phenomena, hardening and softening.

The author of this study develops approaches [2, 3, etc.], in which it is shown that in many cases the mutual dependences of the characteristics noted above can be reduced in a wide range to a simple universal s-shaped function with a small number of defining constants. To describe the most general form of complex nonmonotonic processes of deformation and fracture in a nonlinear region, endochronous hereditary integral equations are constructed that use transformed time with scales - integral functionals with a hierarchical structure. This makes it possible to obtain better agreement with the experimental results, to significantly expand the deformation, fracture, and other functions into the region of short and long times. Efficient methods for rapid testing of samples of various materials for predicting long-term properties in the dynamic and quasi-static regions are proposed and implemented, which make it possible to predict the behavior of materials for dozens of time orders based on the data of very short-term experiments. Examples are given.

References

[1] Semenov A.S. Microstructural and Phenomenological Models of Hysteretic Behavior of Ferroelectroelastic Materials with Allowance for Defects. Proceedings "XII All-Russian Congress on Fundamental Problems of Theoretical and Applied Mechanics". 2019. – V. 3. Mechanics of a Deformable Solid Body. Ufa: BashSU Publ. House. P.- 367-369.
[2] Fedorovsky G.D. On the Physico-mathematical Modelling of the Determining Functional Properties and Interrelationship of Properties of Traditional and Nanostructural Materials // Marine Intelligent Technologies. 2019. № 3-3 (45). P. - 201-207.
[3] Fedorovsky G.D. Development of the Concept of Generalized Time in the Chronomechanics of Deformation and Destruction of Rheologically Complex Functional Materials // Proceedings "XII All-Russian Congress on Fundamental Problems of Theoretical and Applied Mechanics". 2019. – V. 3. Mechanics of a Deformable Solid Body. Ufa: BashSU Publ. House. P. - 392-394.

EFFICIENCY OF NEW STRUCTURAL ELEMENTS BASED ON METAMATERIALS

Fedulov B.N.[1], Fedorenko A.N.[2], Jurgenson S.A.[1], Lomakin E.V.[1]
1 - Lomonosov MSU, Moscow, Russia
2 - Skoltech, Moscow, Russia
fedulov.b@mail.ru

Typically, an essentially low number of standard structural elements used in an engineering practice in general and in civil constructions in particular. As such, examples can be given: beam, plate, shell and their reinforced analogues. Nevertheless, there are approaches that are able to offer the more complex systems of structural elements. For example, using topology optimization methods, it is possible to obtain rather complex variants of structures that are quite unique and are implied in execution only with the support of additive manufacturing technologies. Modern specialists miss opportunities based on such approaches to obtain a system of new and more effective for industry structural elements. Such elements can be standardized, their cost can be reduced, and used in everyday design practice. This research shows examples of the use of new structural elements in application to horizontal slab for construction engineering and plates in general. Their effectiveness of proposed solutions are shown and analyzed.

This work was supported by the Russian Science Foundation under Grant No. 20-11-20230.

SPECIAL MODES OF AXISYMMETRIC VIBRATIONS OF THE CYLINDRICAL SHELL LOADED WITH PERIODIC MASSIVE RINGS

Filippenko G.V.
Institute of Mechanical Engineering, St.-Petersburg, Russia
g.filippenko@gmail.com

Cylindrical shells in liquids have long been investigated in connection with their extensive applications in engineering and construction. This is one of the most important elements in the modeling of acoustic waveguides, various pipelines, supports for offshore rigs and other hydraulic structures [1].

A variant of the classical Kirchhoff-Love shell theory based on analytical Lagrange mechanics [2, 3] was used in this work. This theory, in particular, was used in [4] to study the wave processes and vibrations of the shells of rotation with an arbitrary meridian.

The mentioned theory of shells was also applied in works devoted to a loaded shell. An acoustic fluid [5], Winkler base [6], inertial forces generated by massive "belts" [7] are the examples of such loads. The axisymmetric wave processes are of particular interest, due to both their frequent occurrence and the convenience of analytical analysis. These oscillations are forced by axisymmetric loads. The presence of a concentrated mass, significantly affects the vibrations of the shell.

The purpose of this work is to investigate the vibrations of a circular cylindrical shell with additional inertia in the form of periodic "mass belts" of zero width. The shell is assumed to be infinite and its free harmonic vibrations are considered. On the basis of the exact analytical Floquet solution, the character of dispersion curves is investigated, as well as the field analysis in the vicinity of special points, where a sharp change of oscillations character is occurred.

References
1. El-Reedy M. Offshore Structures: Design, Construction and Maintenance. 2012. 664 p.
2. Eliseev V.V. Mechanics of Deformable Solids. 2003. St. Petersburg, Polytechnic University Press. 336 p. (rus.)
3. Eliseev V.V. Zinovieva T.V. Lagrangian mechanics of classical shells: theory and calculation of shells of revolution. 2018. Shell Structures: Theory and Applications, Vol. 4. pp. 73–76.
4. Zinovieva T.V. Smirnov K.K., Belyaev A.K. Stability of Corrugated Expansion Bellows: Shell and Rod Models. 2019. Acta Mechanica, Vol. 230. pp. 4125–4135. Doi: 10.1007/s00707-019-02497-6.
5. Filippenko G. V. Energy-flux analysis of the bending waves in an infinite cylindrical shell filled with acoustical fluid. 2017. Advances in Mechanical Engineering, Lecture Notes in Mechanical Engineering. pp. 57-64. Doi: 10.1007/978-3-319-53363-6.
6. Filippenko G.V., Wilde M.V. Backwards waves in a cylindrical shell: comparison of 2D shell theories with 3D theory of elasticity. 2018. Proc. of the XLVI Summer School_Conference Advanced problems in mechanics (APM2018). pp. 79-86.
7. Filippenko G.V., Zinovieva T.V. Axisymmetric Vibrations of the Cylindrical Shell Loaded with Pointed Masses. 2021. Advances in Mechanical Engineering. MMESE 2020. Lecture Notes in Mechanical Engineering. Springer, Cham. pp. 80-91. Doi: 10.1007/978-3-030-62062-2_9.

DIRECT NUMERICAL SIMULATION OF THE TWO-DIMENSIONAL COHERENT VORTEX IN A VISCOUS MEDIA

Doludenko V.N.[1], Denisenko V.V.[2], Fortova S.V.[2]
1 - Joint Institute for High Temperatures of the Russian Academy of Sciences (JIHT RAS), Moscow, Russia
2 - Institute of Computer Aided Design of the Russian Academy of Sciences, Moscow, Russia
sfortova@mail.ru

Turbulence in liquid and gas is the most common type of flow in the nature. Such the flow is, of course, a three-dimensional phenomenon. However, for example, in the Earth's atmosphere, such three-dimensional flows can be considered as quasi-two-dimensional flows. This can be done quite rightly because of the small height of the troposphere compared to both the dimensions of the formed vortex structures and the distances over which they move.
The main feature of a two-dimensional turbulent flow, constantly excited by an external force, is the appearance of an inverse energy cascade. Due to nonlinear effects, the spatial scale of the vortices, created by the external force, increases until the growth is stopped by the size of the cell. In the latter case, energy is accumulated at these dimensions. Under certain conditions, accumulation leads to the appearance of a system of coherent vortices. The observed vortices are of the order of the box size and, on average, are isotropic. Numerical simulation is an effective way to study such the processes. Of particular interest is the problem of studying the viscous fluid turbulence in a square cell under excitation by a short-wave and long-wave static external forces. Numerical modeling was carried out with a weakly compressible fluid in a two-dimensional square cell with zero boundary conditions. The work shows how the flow characteristics are influenced by the spatial frequency of the external force and the magnitude of the viscosity of the fluid itself. An increase in the spatial frequency of the external force leads to stabilization and laminarization of the flow. At the same time with an increased spatial frequency of the external force, a decrease in viscosity leads to the resumption of the mechanism of energy transfer along the inverse cascade due to a shift in the energy dissipation region to a region of smaller scales compared to the pump scale.
In this paper, the study was carried out by direct numerical simulation of the system of Navier-Stokes equations by the numerical McCormack method using a model of a weakly compressible fluid. The flow was considered in a two-dimensional square cell with adhesion boundary conditions. The development of the flow occurs due to the presence of the constant acting force, which is periodically acting in OX and OY directions.
The analysis of external force value and bottom friction coefficient influence on the flow pattern and its characteristics has been carried out. It is shown that increasing of external force value turbulizes the flow. Whereas the increase of friction coefficient against the bottom leads to flow stabilization and formation of laminar mode. Thus, different types of flow are observed depending on the value of external force and coefficients of friction against the bottom.
This made it possible to construct a flow diagram in the space "external force - bottom friction" on the basis of generalization of the obtained results.

References
1. Kraichnan R.H. Inertial Ranges in Two-Dimensional Turbulence // Phys. Fluids. 1967. Vol. 10. P. 1417. (1)
2. Batchelor G.K. Computation of the Energy Spectrum in Homogeneous Two- Dimensional Turbulence // Phys. Fluids. 1969. Vol. 12, № Suppl. II. P. 233. (2)
3. Kolokolov I. V., Lebedev V. V. Large-scale flow in two-dimensional turbulence at static pumping // JETP Lett. 2017. Vol. 106, № 10. P. 659–661.(3)
4. Doludenko, A.N., Fortova, S.V., Kolokolov, I.V., Lebedev, V.V. Coherent vortex in a spatially restricted two-dimensional turbulent flow in absence of bottom friction // Physics of Fluids. – 2021. – V. 33. – Paper 011704.

KINETICS AND STABILITY OF CHEMICAL REACTION FRONTS IN DEFORMABLE SOLIDS

Freidin A.B.
Institute for Problems in Mechanical Engineering of the Russian Academy of Sciences, St. Petersburg, Russia
alexander.freidin@gmail.com

Coupled problems of chemo-mechanics are discussed for chemical reactions between diffusing and solid reactants. A reaction is localized at the reaction front that divides solid constituents, e.g. [1,2]. As it was derived (see the reference in [3]), the configurational force driving the reaction front is determined by a chemical affinity tensor which is a combination of chemical potential tensors of solid constituents and a chemical potential of a diffusing constituent. Two types of reactions are highlighted: stress-affected reactions which can go without stresses, and stress-induced reactions which can go only under a proper loading. Examples of solving coupled problems "diffusion–chemistry–mechanics" are given which demonstrate how the mechanical stresses can accelerate, retard and block the reaction front propagation. Then the stability of the reaction front is examined on the basis of the developed analytical procedures of the stability analysis and numerical simulations of the front propagation. The competition between the global microkinetic of the reaction front and the local kinetics of the front perturbations far and near the front blocking position is discussed.
The financial support of the Russian Science Foundation is acknowledged (Grant 19-19-00552).

References
[1] Heidemeyer, H. et al, Self-limiting and pattern dependent oxidation of silicon dots fabricated on silicon-on-insulator material, Journal of Applied Physics, 87, 4580–4585 (2000).
[2] McDowell, M.T. et al, In situ TEM of two-phase lithiation of amorphous silicon nanospheres, Nano Letters, 13, 758–764 (2013).
[3] Freidin, A.B., Vilchevskaya, E.N., Chemical affinity tensor in coupled problems of mechanochemistry, Encyclopedia of Continuum Mechanics. Altenbach, H. and Öchsner, A. (Eds) Berlin, Heidelberg, Springer Berlin Heidelberg (2020).

PROBLEMS OF VORTEX FLUID DYNAMICS

Gaifullin A.M.
Central Aerohydrodynamic Institute
amgaif@mail.ru

A number of problems of vortex fluid dynamics related to submerged jets and the interaction of vortex flows with solid surfaces and acoustic disturbances are considered: axisymmetric jets with flow through the initial section, swirling jets, three-dimensional wall jets, the interaction of a plane acoustic wave with a vortex flow. Two objectives of this report can be distinguished. The first is to present new theoretical results of the study of vortex flows. The second goal is probably more important than the first. The thing is this: despite the fact that many well-known hydrodynamicists took part in the creation of theories of jet flows and the interaction of vortex flows with solid surfaces and acoustic disturbances, this field of hydrodynamics, like perhaps no other, is replete with erroneous statements and results. Many of these statements and results over the years are perceived by the scientific community as true. The situation is aggravated by the fact that errors on this topic are present both in well-known monographs and in widely cited articles. Detecting these erroneous results and replacing them with correct statements is the main goal of the report.

MODELING OF THERMOVISCOUS LIQUID FLOW IN A CONICAL DIFFUSER

Galeeva D.R.[1], Kireev V.N.[1], Urmancheev S.F.[2]
1 - Bashkir State University, Ufa, Russia
2 - Mavlutov Institute of Mechanics, Ufa, Russia
lara_wood@mail.ru

Diffuser is a section of pipelines, on which there is a smooth increase in the pipeline cross section. Diffusers are widely used in devices of chemical, oil, food and other industries to convert dynamic pressure into static pressure by slowing down the main flowrate. Various aspects of the flow in diffusers are studied in a huge number of theoretical, experimental and applied publications. In particular, the regularities of turbulent mixing in tubular chemical reactors of the diffuser-confuser type are studied in work [1]. In paper [2], it is proposed to use pipelines with a periodically changing cross section to improve the efficiency of pumping hydrocarbon liquids in transport systems. In practice, diffusers can be subjected to external thermal effects, which affect the flow parameters. The paper [3] proposes a refined approach to the calculation of the coefficient of local hydraulic resistance to the flow of a viscous fluid in a flat channel with a stepped narrowing under external thermal action.
In the present work, the effect of non-uniform temperature field on the laminar flow of an incompressible fluid with the temperature-dependent viscosity in a conical diffuser is studied. It is assumed that the liquid flowing into the diffuser has a constant temperature and the diffuser wall is maintained under another constant temperature.

The mathematical model consists of the continuity equation, the Navier-Stokes equations and the energy conservation equation, written in a cylindrical coordinate system, taking into account axial symmetry. Temperature dependence of viscosity is taken in a form of monotonic and non-monotonic functions.
The equations of the mathematical model are solved numerically by the Finite Volume Method using the SIMPLE algorithm [4], which is modified to take into account the variable viscosity coefficient. The computer code is implemented in the Pascal programming language using the Delphi development environment and it is validated by comparing the numerical and analytical solutions [5] for the case of a liquid with constant viscosity.
As a result of numerical simulation, the velocity, temperature, and viscosity fields in the diffuser channel are obtained, as well as the velocity profiles of the thermoviscous liquid flow for various sections. The influence of the channel geometry, temperature field, and parameters of the temperature dependence of viscosity on the hydrodynamic characteristics of the flow in a diffuser is studied.
The research is supported by the Russian Science Foundation (Project No. 22-21-00915).
References
1. Takhautdinov R.G., Dyakonov G.S., Deberdeev R.Ya., Minsker K.S. Turbulent mixing in small-sized devices of chemical technology // Khimicheskaya promyshlennost'. – 2000. No. 5. Pp. 41-49 [in Russian].
2. Khabibullin M.Ya. Study of liquid flow processes in pipeline with changing diameter // Problemy sbora, podgotovki i transporta nefti i nefteproduktov. 2019. No. 1. – Pp. 89-95. [in Russian]
3. Nizamova A.D., Kireev V.N., Urmancheev S.F. To the calculation of the channel local hydraulic resistance with external heating // Vestnik UGATU. 2021. Vol. 25, No. 3. Pp. 34-41. [in Russian]
4. Patankar S. Numerical Heat Transfer and Fluid Flow. New York: Hemishere Publishing Corporation, 1980. 199 p.
5. Slezkin N.A. Dynamics of a viscous incompressible fluid. Moscow: Gostekhizdat, 1955. 520 p. [in Russian]

TO THE THEORY OF FRACTURE PROBING BY THE ACOUSTIC "TV" METHOD

Shagapov V.Sh.[1], Galiakbarova E.V.[1,2], Chakimova Z.R.[1,2]
1 - Malyutov Institute of Mechanics—a separate structural subdivision of the Ufa Federal Research Center, Russian Academy of Sciences, Ufa, Russia
2 - Ufa State Oil Technical University, Ufa, Russia
emi.galiakbar@yandex.ru

Theoretical constructions show the possibility of diagnosing the presence and conductivity of hydraulic fractures in formations with permeability of the order of centi- and millidarsi using an acoustic "TV", representing a cylindrical probe several meters long with a pulse signal generator and pressure sensors. It is assumed that the pulse signal is created in the fluid in the channel between the probe body and the open borehole wall. The evolution of the signal recorded by the pressure transducers in the form of attenuation of its amplitude and the appearance of reflected pressure bursts, allows to estimate the presence and conductivity of fractures in the bottomhole zone. The fractures that are longitudinal or perpendicular to the open section of the well are considered. In the theoretical model, the pulse signal wavelength is smaller than the probe length, but larger than the channel size. The attenuation of the pulse signal due to viscosity in the boundary layer near the channel walls is taken into account. The crack thickness is much less than the wavelength, so the perpendicular crack is assumed to be a reflecting surface. The results of dispersion analysis and numerical experiments on the influence of filtration characteristics of fractures, reservoir, channel size and fluid type on the evolution of pulse signals in the channel are presented.
Highlights of the article
- A theoretical model of the dynamics of the pulse signal in the channel between the cylindrical probe and the open section of the well with acoustically compressible fluid, taking into account the filtration of the fluid into fractures, longitudinal or perpendicular to the well, as well as into the formation, is proposed to study the diagnostic capabilities of hydraulic fractures.
- The influence of filtration characteristics of fractures, formation, channel size and fluid type on dependences of phase velocity and attenuation coefficient, as well as reflection and passage coefficients for perpendicular fractures, on circular frequency using analytical and numerical solutions is analyzed.
- The results of numerical experiments based on fast Fourier transform algorithms on the evolution of the impulse signal in a channel surrounded by a centi- and millidarcy permeability layer filled with water allow diagnosing the presence and conductivity of cracks.
The study was partially supported by a grant from the Russian Science Foundation (project no. 21-11-00207) https://rscf.ru/project/21-11-00207/.

ANALYTICAL AND NUMERICAL SOLUTION OF THE PROBLEM OF HYDROGEN DIFFUSION IN ROTATING CYLINDRICAL ELASTIC BODIES

Belyaev A.K., Galyautdinova A.R., Smirnov S.A., Bessonov N.M.
Institute for Problems in Mechanical Engineering of the Russian Academy of Sciences
aliyagalyautdinova@gmail.com

The work is devoted to the solution of the problem of hydrogen diffusion in rotating cylindrical elastic bodies compressed by two distributed loads. The study includes the analytical determination of the stress state of the body, the derivation of the hydrogen diffusion equation in a rotating body in the field of elastic stresses and the numerical solution of the obtained hydrogen diffusion equation.
The determination of the stress state of the body was carried out on basis of known stresses from the Hertz contact problem of the compression of two cylinders initially touching along a line. In addition, the theory of functions of a complex variable and approximating methods were used to obtain an approximate analytical expression for average normal stresses. The numerical solution of the diffusion equation was carried out by the method of finite differences. To solve the difference problem the tridiagonal matrix algorithm was used. Numerical solution of the problem took into account various boundary conditions.
According to the numerical solution of the diffusion equation, the effect of hydrogen concentration localization near the outer boundary was detected. This result is consistent with experimental studies of the distribution of hydrogen concentration in roller bearings. This problem is important for diagnostics of failures of rolling bearings due to hydrogen embrittlement. The research is carried out under the financial support by Russian Science Foundation, grant 18-19-00160.

UNSTEADY BALLISTIC HEAT TRANSPORT IN A 1D HARMONIC CRYSTAL DUE TO A SOURCE ON AN ISOTOPIC DEFECT

Shishkina E.V., Gavrilov S.N.
IPME RAS, St. Petersburg, Russia
serge.gavrilov@gmail.com

In the paper we apply asymptotic technique based on the method of stationary phase and obtain the approximate analytical description of thermal motions caused by a source on a isotopic defect in a 1D harmonic crystal. It is well known that localized oscillation is possible in this system in the case of a light defect. We consider the unsteady heat propagation and obtain formulae, which provide
continualization and asymptotic uncoupling of the thermal motion into the sum of the slow and fast components, everywhere excepting a neghbourhood of a defect. The slow motion is related with ballistic heat transport, whereas the fast motion is energy oscillation related with transformation of the kinetic energy into the potential one and in the opposite direction. To obtain the propagating component of the fast and slow motions we estimate the exact solution in the integral form on a moving point of observation. We demonstrate that the propagating part of the slow motion is ``anti-localized'' near the defect. The physical meaning of the anti-localization is a tendency for the unsteady propagating wave-field to avoid a neghbourhood of a defect. In the case of a light defect it is necessary to take into account also a localized non-propagating component, which traps some
portion of energy forever. The effect of anti-localization increases with absolute value of the difference between mass of the isotope and mass for other particles, and, therefore, more energy concentrates just behind the leading wave-fronts of the propagating component.

WAVE PHENOMENA IN MULTI-LAYERED ACOUSTIC METAMATERIALS WITH ARRAYS OF PLANAR CAVITIES OF CRACK-LIKE TYPE

Golub M.V.[1], Doroshenko O.V.[1], Fomenko S.I.[1], Yanzheng W.[2], Zhang C.[2]
1 - Kuban State University, Krasnodar, Russia
2 - Siegen University, Siegen, Germany
m_golub@inbox.ru

Last decades, acoustic/elastic metamaterials (AMMs), which exhibit unusual properties has received special attention since they can provide wave energy manipulation. AMMs usually have periodical or quasi-periodical structure, where various inhomogeneities are composed into arrays. In the present study, layered AMMs with planar cavities, cuts or cracks are considered. Two numerical methods are applied to simulate different configurations of AMMs with the considered kind of inhomogeneities. The boundary integral equation method is employed to simulate wave phenomena such as a band-gap formation or opening of an interface for wave propagation in unbounded multi-layered AMM with a doubly periodic array of inhomogeneities. The spectral element method is adopted and applied to calculate the transmission coefficients for guided elastic waves propagating in layered AMMs of finite size with arrays of thin planar cavities. It is shown that extra band-gaps are generated due to the introduction of such periodic arrays of cavities, especially some of them are in the low-frequency ranges. The influence of the AMM configuration on wave propagation is analysed. The manufacturing of the proposed configurations of AMMs and application of such structures as wave filters is discussed.

PHYSICAL MECHANISMS AND REGULARITIES OF ULTRASONIC DRILLING OF UNKNOWN GROUND (BEFORE THE LANDING) OF SPACE OBJECTS IN EXTREME CONDITIONS

Khmelev V.N.[1], Golykh R.N.[1], Quan Q.[2], Barsukov R.V.[1], Jiang S.[2], Genne D.V.[1], Junwei L.[2]
1 - Biysk Technological Institute (branch) of Altai State Technical University named after I.I. Polzunov, Biysk, Russia
2 - Harbin Institute of Technology, Harbin, China
romangl90@gmail.com

One of the main problems of performing research on small celestial bodies with low gravity (asteroids and satellites of distant planets) is the need to fix the lander on the surface by drilling unknown soil properties. To solve the problem, the use of ultrasonic drilling is currently being proposed. When placing ultrasonic devices on the supports of the lander, such drilling allows:
– more effective destroying the soil in comparison with known mechanical methods (drilling, chiseling, etc.) with reduced parasitic heating to exclude evaporation or sublimation of traces of water, volatile substances. The addition of ultrasonic effects by pseudo-rotation and low-frequency vibrations will provide a significant acceleration of the process of securing the lander;
– determine the composition and properties of the soil in real time by changing the impedance of the “ultrasonic radiator-soil” system to optimize the modes of ultrasonic and additional exposure.
The authors of the report proposed and substantiated the physical mechanism of ultrasonic drilling of extraterrestrial soil.
The developed physical and mathematical model of ultrasonic destruction and deformation of solid soil is implemented as a computer program for calculating the process of deformation and destruction of soil and allows numerical calculations of the effect of soil properties on the impedance characteristics of the ultrasonic emitter. The model takes into account the presence of additional influences (shock, rotational) and external loads (at different angles to the axis of the emitter).
The performed studies have allowed us to evaluate that at small amplitudes of vibrations that do not cause soil destruction, the elastic modulus of the soil has a significant effect on the cosine of the phase shift angle between the force and the displacement velocity. For example, with an oscillation amplitude of 3 microns, the cosine of the phase shift angle decreases by almost 2 times with an increase in the elastic modulus from $1 \cdot 10^{10}$ to $5 \cdot 10^{10}$ Pa.
The obtained results allow to create a method for controlling the properties and type of extraterrestrial soil in real time without using external sensors (the ultrasonic drill itself serves as a sensor) to select optimal influence modes that ensure maximum drilling speed.
The analysis of the influence of ultrasonic drilling modes on the rate of soil destruction made it possible to establish the limiting possibilities of ultrasonic drilling (the existence of oscillation amplitudes, starting from which the drilling speed of the soil stops growing) and to identify local maxima of drilling speed at a constant electric power consumption of the drill. In particular, it was evaluated that the distance between local maxima is from 9 to 11 kHz, and drilling speed maxima are provided at frequencies of 11 kHz and 21 kHz.
Piezoelectric oscillatory systems with ultrasonic generators capable of operating at cosmic temperatures have been developed and manufactured for experimental confirmation of the results.
The research was carried out with the financial support of RFBR and NSFC within the framework of the scientific project 21-52-53036 “Physical mechanisms and regularities of ultrasonic drilling of unknown ground (before the landing) of space objects in extreme conditions”.

REDUCED COSSERAT VISCOELASTIC MEDIUM WITH COMBINED TYPE OF VISCOSITY AS AN ACOUSTIC METAMATERIAL

Barsukov S.S.[1], Grekova E.F.[2,1]
1 - Peter the Great St. Petersburg Polytechnic University
2 - Institute for Problems in Mechanical Engineering of the Russian Academy of Sciences
elgreco@pdmi.ras.ru

We consider a linear isotropic viscoelastic reduced Cosserat medium, i.e. a linear isotropic viscoelastic micropolar continuum that does not react on the gradient of microrotation. We introduce the viscosity of Kelvin-Voight type, as it is done by A.C. Eringen. For zero dissipation such an elastic medium, as it was shown before, is a single negative acoustic metamaterial with respect to the shear waves: it has a bandgap for running plane shear harmonic waves. Viscosity changes essentially its wave properties. We may introduce translational viscosity proportional to the symmetric part of the gradient of translational velocity, and rotational viscosity, proportional to the difference of velocities of micro- and micro-rotation. In works by A. Pyatysheva and E. Grekova these two cases were considered separately, and it was shown that each one of these types of dissipation yields in existence of travelling plane harmonic shear wave with decreasing amplitude at all frequencies, and that for small translational dissipation as well as for small rotational dissipation in the former bandgap there exist a decreasing part of the dispersion curve, corresponding to the zone of anomalous refraction. Now we consider this medium for the combined type of dissipation. We obtain that again the travelling shear wave exist at all frequencies, and that for small friction the medium converts into a double negative acoustic metamaterial in a certain frequency domain for shear waves (i.e. there is a zone of anomalous refraction). Qualitatively the case of combined infinitesimal dissipation is more close to the case of infinitesimal rotational dissipation: the cut-off frequency, present in the elastic case and in the case of translational viscosity, disappears, anomalous refraction takes place in the lower part of the former bandgap, but does not take the whole zone (contrary to the case of translational dissipation). We see that the influence of both parameters depends on frequency. At low frequencies the translational dissipation plays the principal role. Not far from the former cut-off frequency the rotational dissipation prevails. For high frequencies as well as near the former boundary frequency both dissipation parameters are important. Logarithmic decrement in the former bandgap decreases while the infinitesimal dissipation decreases, and imaginary part of the wave number may have both type of behaviour depending on the material parameters and frequency.

HYDROGEN DIFFUSION IN STEELS AND ITS MUTUAL INFLUENCE ON THE MECHANICAL STRESS FIELDS

Grigoreva P.M.[1], Polyanskiy V.A.[2]
1 - Peter the Great St.Petersburg Polytechnic University, Russia
2 - Institute for Problems in Mechanical Engineering of the RAS, St.Petersburg, Russia
polina.grigoreva239@gmail.com

The effect of hydrogen degradation on the strength properties of metals has been in the focus of mechanics for more than a hundred years. Recent experimental estimates and measurements of the hydrogen concentration profile in metals show that the concentration of hydrogen in the boundary layer is tens or even hundreds of times higher than the concentration of hydrogen in the entire volume of the metal, and suggests that this thin layer with a thickness of about a micrometer has the strongest effect on the elastic properties, brittleness and viscosity of the metal. Thus, the modeling of the formation of a hydrogen thin boundary layer and the description of the mutual influence of the diffusion process on the mechanical properties of the metal is of considerable theoretical and practical interest.

There is still no definitive certainty on how to take into account the influence of mechanical stresses on diffusion. Models based on the thermodynamics of irreversible processes have become widely used, according to which the diffusion rate is proportional to the change in the volume or stiffness of a solid material or to the change in the concentration of a gas. In a number of works, the diffusion rate is expressed through the chemical potentials of materials, using the Eshelby tensor as the chemical potential of a deformable solid. Such models, however, have certain difficulties associated with the definition of model constants. In addition, experiments show that hydrogen not only diffuses through the crystalline substance of the metal, but is also redistributed in trap modes. Therefore, the diffusion of hydrogen in metals should be considered not only as an ordinary diffusion along grain boundaries. On the other hand, many works devoted to the diffusion of hydrogen in metals consider this diffusion exclusively as occurring with the help of a trap mechanism. Such models are specific and do not adequately describe all the various experimental data. This leads to the fact that the hydrogen diffusion coefficients in the reference books are indicated with an accuracy of up to an order of magnitude. It should also be noted that most trap and volume diffusion models have been verified for small gradients of hydrogen concentration in the material. This does not allow taking into account the observed boundary layer and requires significant modification of these models.

For a more accurate description of the experimentally observed near-surface layer with a high concentration of hydrogen, which is relatively stable in time and does not expand deep into the metal due to diffusion, this paper considers the equation of hydrogen transport into the metal in a stress-strain state, obtained within the framework of the approach of linear nonequilibrium thermodynamics, with an additional introduced drain term. Two possibilities of introducing a stock member were considered. The first of them is the classic McNabb model. As an alternative, another model of two-channel diffusion was proposed, which separately takes into account the flow through inhomogeneities inside the metal. One-dimensional and plane problems, the effect of linear and plastic stresses on diffusion are considered, and the possibility of using the obtained models to describe the experimentally observed hydrogen boundary layer is evaluated.

The research is supported with RFBR grant, project number 20-08-01100.

DEVELOPMENT OF THE FORMALISM OF DISCRETE ELEMENTS FOR THE STUDY OF WEAR PARTICLE FORMATION IN CONTACT BETWEEN SLIDING METALS

Grigoriev A.S., Shilko E.V., Smolin A.Yu.
Institute of Strength Physics and Materials Science SB RAS
grigoriev@ispms.ru

Adhesive wear during sliding friction of dry surfaces has been intensively studied over the past several decades. Nevertheless, it is still a phenomenon extremely difficult to understand and predict. One of the most popular approaches to understanding and interpretation of key aspects of friction and wear is the concept of the third body. This concept implies the formation and development of material fragments (interfacial elements) between contacting surfaces and the determining contribution of these elements to the dynamics of contact interaction including the value of the friction coefficient and wear rate. These effects are especially pronounced in metallic friction pairs due to the high values of surface energy and ductility of metallic materials.

We proposed a new discrete-element mechanical model, which allows the numerical study of contact interaction of ductile materials with taking into account fracture and surface adhesion by the cold welding mechanism. The model describes these competitive processes from a unified standpoint and uses plastic work of deformation as a criterion of both local fracture and chemical bonding of surfaces in contact spots. This allows modeling the formation of the third body (wear particles and wedges) during the friction of rough metal surfaces. The unification ensures the consistency of fracture and bonding models and the unity of the phenomenological description of opposing (competing) processes of fracture and cold welding under the contact interaction of ductile materials.

Using the developed model, we numerically studied the formation of wear particles and wedges during the friction and the influence of the type of forming third body elements on the dynamics of the friction coefficient in Cu-Al bronze tribounit. We revealed the qualitative difference of friction dynamics in the areas of the contact zone characterized by different degrees of mechanical confinement. In particular, we have shown that either rounded particles weakly adhered to surfaces, or wedges/prows are predominantly formed depending on the degree of mechanical confinement of the contact region. Accordingly, the degree of mechanical confinement should largely determine the value of the friction coefficient, as well as the wear rate and the size distribution of wear particles.

A promising way to improve the tribological properties of some alloys (including Cu-Al bronzes) is to realize transformation-induced plasticity by adding alloying elements. To take into account the transformation mechanism of plasticity, we developed a general phenomenological model based on the plastic flow theory and the kinetic model of Lagoudas et al. Using this model, we numerically studied the influence of the transformation mechanism of plasticity on the structure of the third body and friction stability.

The study was funded by the Russian Science Foundation grant No. 20-19-00743, https://rscf.ru/project/20-19-00743.

ORIENTATION DEPENDENCES OF INELASTIC DEFORMATION OF NICKEL-BASED SINGLE-CRYSTAL SUPERALLOYS

Grishchenko A.I., Semenova A.A., Semenov A.S.
Peter the Great St.Petersburg Polytechnic University, St.Petersburg, Russia
gai-gr@yandex.ru

Nickel-based single-crystal superalloys are widely used in aircraft and power turbines. They are practically non-alternative materials for gas turbine engines of the 5th and 6th generation. Their distinguishing features include high characteristics of long-term strength, heat resistance, high resistance to corrosion and high-temperature creep, and anisotropy of mechanical properties [1, 2]. The aim of this work is to analyze the influence of the crystallographic orientation of nickel-based single-crystal alloys on the level of plastic deformations under uniaxial tension.

Based on the rheonomic and scleronomic micromechanical model of inelastic deformation, the orientation dependences of the plastic and creep deformation of a single crystal are obtained and analyzed. The contribution of octahedral and cubic slip systems (SS) is estimated.

1. Semenov A. S., Beliaev M. O., Grishchenko A. I. Modeling of cross-section ovality of single crystal nickel-based superalloy samples under tension / PNRPU Mechanics Bulletin. 2017. n 2. p. 153 – 177

2. Shalin R.E, Svetlov I.L, Kachanov E.B., Toloraiya V.N., Gavrilin O.S. Single crystals of nickel heat-resistant alloys. M.: Mashinostroenie; 1997.

STUDY OF THE DISTRIBUTION OF ENERGY IN DIFFERENT CHAINS

Gruzdev I.E.
Polytechnic University, St.Petersburg, Russia
superigor_2000@mail.ru

In this work a comparative analysis of the movement of an energy center in harmonic monatomic and diatomic crystals, as well as a crystal on an elastic foundation, is carried out. In each case, the equation of motion of the energy center for an arbitrary perturbation with a finite energy is obtained.

It is shown that in the chain of Hook's and a crystal on an elastic foundation, the energy center moves uniformly. In this case, when specifying the first moment of energy for a diatomic chain, it is rather difficult to obtain an exact conservation of the energy flux. It is proved that in a crystal with mass alternation, a similar result can be obtained with a more complex setting of the first moment of energy.

Also, for a Hook's crystal and a chain on an elastic foundation, calculations were made showing that the second derivative of the second moment of energy is a constant. Based on this, one can derive the equations of evolution of the energy radius, which will be an analogue of the radius of gyration in mass dynamics.

Based on this research, an analogy is built between the dynamics of mass and the dynamics of energy.

MISFIT STRESSES DUE TO A CYLINDRICAL DILATATIONAL INCLUSION OF ANNULAR-SECTOR CROSS-SECTION

Gudkina Zh.V.[1,2], Gutkin M.Yu.[2,3,4], Krasnitckii S.A.[2,3,4]
1 - Ioffe Physical-Technical Institute, Russian Academy of Sciences, St. Petersburg, Russia
2 - ITMO University, St. Petersburg, Russia
3 - Institute for Problems in Mechanical Engineering, Russian Academy of Sciences, St. Petersburg, Russia
4 - Peter the Great St. Petersburg Polytechnic University, St. Petersburg, Russia
gudkinazhanna@mail.ru

The study of inclusions is of significance to the development of advanced materials for aerospace, marine, automotive and many other applications [1]. This is because the presence of inclusions in materials affects their elastic fields at the local and the global scale and thus greatly influences their mechanical and physical properties. Analysis of elastic strains induced by misfitting inclusions in an infinite or semi-infinite elastic medium is a fundamental physical and engineering problem [2].

Nowadays, in parallel with further efforts on searching new solutions for inclusions and inhomogeneities of various shapes in different media within the mechanics [1], much attention is paid to their applications in materials science [3] and solid-state physics [4] with special focus on structural and functional nanocomposites [5] and nanoheterostructures for electronics, optoelectronics, photonics, etc. [6]. In particular, of great interest are the inclusions of the shape different from the well-known classical cases of speroidal, ellipsoidal, cuboidal, cylindrical, polyhedral and prismatic shapes. In due course of this trends, we suggest in the present paper a solution for a cylindrical dilatational inclusion of annular-sector cross-section in an elastic infinite medium. Let the inclusion occupy a domain and its elastic constants be isotropic and equal to those of the surrounding matrix. The inclusion domain is a subject of a 3D homogeneous dilatational eigenstrain ε^*.

The solution has been found by simple integration of the solution for an infinite dilatational line (i.e. a straight line subjected to 3D dilatational eigenstrain [7]) over the cross-section area of the inclusion. The solution found is illustrated by maps of all non-vanishing stress components that allow to reveal new interesting features in the stress distribution inside and outside the inclusion. One can conclude that suitable theoretical models for stress relaxation in/around the inclusion are highly desired.

Acknowledgments
The work of G.Zh.V. was partially supported by the Russian Foundation for Basic Research (RFBR), grant no. 19-29-12041 mk.

References

[1] K. Zhou, H.J. Hoh, X. Wang, L.M. Keer, J.H. Pang, B. Song, Q.J. Wang, A review of recent works on inclusions // Mechanics of Materials **60** (2013) 144-158.
[2] B.N. Kuvshinov, Elastic and piezoelectric fields due to polyhedral inclusions // International Journal of Solids and Structures **45(5)** (2008) 1352-1384.
[3] M. Doi, Elasticity effects on the microstructure of alloys containing coherent precipitates // Progress in Materials Science **40(2)** (1996) 79-180.
[4] A.P. Chernakov, A.L. Kolesnikova, M.Yu. Gutkin, A.E. Romanov, Periodic array of misfit dislocation loops and stress relaxation in core-shell nanowires // International Journal of Engineering Science **156** (2020) 103367.
[5] S. Krasnitskii, A. Trofimov, E. Radi, I. Sevostianov, Effect of a rigid toroidal inhomogeneity on the elastic properties of a composite // Math Mech Solids **24(4)** (2019) 1129-1146.
[6] F. Glas, Strain in nanowires and nanowire heterostructures // Semiconductors and Semimetals **93** (2015) 79-123.
[7] A.L. Kolesnikova, R.M. Soroka, A.E. Romanov, Defects in the elastic continuum: classification, fields and physical analogies // Mater Phys Mech **17(1)** (2013) 71-91.

DISCLINATION-BASED MODELS OF FAST FORMATION AND SLOW DISSOLUTION OF PORES AT GRAIN BOUNDARIES DURING ANNEALING OF AN ULTRAFINE-GRAINED ALUMINUM ALLOY

Gutkin M.Yu.[1], Orlova T.S.[2], Skiba N.V.[1,3]
1 - Institute for Problems in Mechanical Engineering, Russian Academy of Sciences, St. Petersburg, Russia
2 - Ioffe Institute, Russian Academy of Sciences, St. Petersburg, Russia
3 - Peter the Great St. Petersburg Polytechnic University, St. Petersburg, Russia
m.y.gutkin@gmail.com

Ultrafine-grained (UFG) alloys often have high strength combined with sufficient plasticity due to the presence of nanoscale precipitates [1,2]. In experiments [3–5], an accelerated precipitation of the second phase was revealed in UFG materials obtained by methods of severe plastic deformation. In particular, a significant amount of nanoscale precipitates of the Al_3Zr phase was observed in the UFG Al-Zr alloy, obtained by the high pressure torsion method and then annealed at 230 °C [5]. However, the reasons for the accelerated kinetics of the precipitation remain poorly understood. In due course of annealing this alloy *in situ* in a scanning transmission electron microscope, Lefebvre et al. [6] found, during the first 10 min of annealing, multiple formation of pores along grain boundaries (GBs) and their triple junctions (TJs). At the second (long-term, for 3 h) stage of annealing, gradual dissolution of pores was observed up to the complete disappearance of some of them [6]. Such dissolution of pores, accompanied by the emission of vacancies, can promote accelerated precipitation in UFG structures.
To explain these observations, we suggest some theoretical models. In particular, first, we describe the pore formation at TJ and GB disclinations as a thermodynamically driven process of free volume dissolution through generation of vacancies which then migrate to the disclinations and coagulate at them with growth of the pores diminishing the disclination strain energy. We have calculated the equilibrium pore radius and the critical pore radii, in the range of which the pore existence is energetically favorable at a disclination. We have shown that both the equilibrium pore radius and critical pore radii interval increase with the strength of the disclination. We have also demonstrated that the free volume stored in the nonequilibrium GBs, adjacent to a TJ, is large enough for creation of an observable pore at the TJ during fast transformation of the GBs into more equilibrium GBs under fast annealing.
Second, we describe a further decrease of the TJ and GB disclination strain energy through the climb of extrinsic GB dislocations towards the disclinated TJ and GB pores, accompanied with dissolution of the pores by emission of vacancies which assist the dislocation climb in the course of long-term annealing. In the framework of the model, we have calculated the energy differences, caused by the shrinkage of the disclination structure around a disclinated pore, and shown that this shrinkage is energetically favorable. The proposed mechanism of pore dissolution in UFG materials is in good agreement with the available experimental data [4–6].
The revealed features of the GB structure evolution during low-temperature annealing of UFG Al-Zr alloys opens a new GB engineering approach to increase the strength of these materials at elevated temperatures.

[1] X. Sauvage, G. Wilde, S.V. Divinski, et al., Mater. Sci. Eng. A 540 (2012) 1.
[2] A. Deschamps, G. Fribourg, Y. Bréchet, et al., Acta Mater. 60 (2012) 1905.
[3] X. Sauvage, A. Duchaussoy, G. Zaher, Mater. Trans. 60 (2019) 1151.
[4] Y. Nasedkina, X. Sauvage, E.V. Bobruk, et al., J. Alloys Compd. 710 (2017) 736.
[5] T.A. Latynina, A.M. Mavlyutov, M.Y. Murashkin, et al., Philos. Mag. 99 (2019) 2424.
[6] W. Lefebvre, N.V. Skiba, F. Chabanais, et al., J. Alloys Compd. 862 (2021) 158455.

DILATOMETRY STUDY OF FE-CU WITH DIFFERENT CONCENTRATIONS OF MULTIWALLED CARBON NANOTUBES AND DIFFERENT MILLING TIMES

Bouleklab M.C.[1], Naoui Y.[1], Barama N.[1], Khelil S.[1], Dorbani T.[1], Revo S.[2], Hamamda S.[1]
1 - Frère Mentouri Constantine 1 University, Algeria
2 - Taras Shevchenko National University of Kyiv, Ukraine
shamamda@yahoo.com

The presented work aims to study the effect of incorporating different concentrations of multiwall carbon nanotubes into iron-copper (Fe–Cu) with a ratio of 4:1; MWCNTs of 0.5, 1.0 and 2.0 vol.% of nanocomposites made via mechanical milling of different times of 20, 60 and 120 minutes on the thermal and structural properties.
For the evaluation and characterizations, multiple instruments were used such as the Jupiter STA 449 F3 NETZSCH for measuring the heat flow and the weight change (thermogravimetry), as for the relative linear expansion and coefficient of linear thermal expansion (CTE) the NETZSCH 402C dilatometer was used, all-temperature dependences measurements were conducted from ambient temperature up to 800 °C with a heating rate of 10 °C/min. On the other hand, the evaluation of the structural changes was carried out by using the automated Philips X Pert Pro diffractometer in the monitoring range of [20–80°] with a step scan of 0.026°. Raman spectroscopy was carried out by using a Raman Bruker Senterra spectrometer instrument, with a green laser (wavelength λ= 532 nm) from an argon ion. The infrared absorption was done by using the Jasco FT/IR-6300 spectrometer.
Several temperature ranges were distinguished for the Fe–Cu–X%MWCNTs nanocomposite by the (T) and CTE

temperature dependences. The effect of CNTs on the CTE temperature dependences is changed for different temperature ranges, and the magnitude of the effect depends on the CNTs content.
The heat flow and thermogravimetry show thermal stability and higher calorific capacity for the samples with longer milling time and containing a higher concentration of CNTs.
As for the coefficient of thermal expansion, improved CTE of the Fe–Cu-1% MWCNs milled for 120 minutes.
The provided x-ray diffraction patterns show a grain refinement for the 120 minutes milling time, also a homogenous distribution of CNTs (the absence of CNTs clusters appearing as carbon graphite)
Raman spectroscopy, on the other hand, assessed the CNTs morphology integrity and damage state due to the milling time, it reveals a higher defect density with longer milling time, with an exception for the 60 minutes it shows a lower defect density which indicates the healing and the recovery of CNTs.
The presence of functional groups in the samples is showed using Infrared spectroscopy, in addition of the establishment of multiple bonding types.

EFFECT OF SINGLE (SIC OR NB_2O_5) AND HYBRID (AL_2O_3/SIC) REINFORCEMENTS ON MECHANICAL PROPERTIES OF MG MATRIX COMPOSITES PROCESSED BY STIR CASTING METHOD AND ECAP PROCESSING

Huang S.-J.[1], Addisu N.A.[2], Subramani M.[1], Kannaiyan S.[1], Mose M.P.[1], Borodianskiy K.[3], Chiang C.-C.[1]
1 - Department of Mechanical Engineering, National Taiwan University of Science and Technology, Taipei, Taiwan
2 - Faculty of Mechanical and Industrial Engineering, Bahir Dar University, Bahir Dar, Ethiopia
3 - Department of Chemical Engineering, Ariel University, Ariel, Israel
sgjghuang@mail.ntust.edu.tw

Magnesium matrix composites are light in weight compared to other metals matrix composites and can be used for different structural, biomedical and thermal management applications [1,2]. To enhance the mechanical and microstructural properties of Mg matrix composites the most cost-effective approach is to use reinforcing particles [3,4]. The reinforcing of Mg matrix composites can be achieved by using single or hybrid reinforcements. In this work, the effects of single (SiC or Nb2O5), and hybrid (Al2O3 and SiC) reinforcing particles on the mechanical and microstructural properties of Mg matrix composites were investigated [5–8]. The composites were fabricated by using stir casting method with a controlled casting environment to prevent the Mg burning and oxidation. The casted samples were subjected to homogenization heat treatment at 400°C for 24hrs to dissolve casting induced secondary phases [7]. The heat-treated samples were deformed by using equal channel angular pressing (ECAP) to significantly improve microstructural and mechanical properties of composites. The microstructural morphology scanning electron microscope (SEM) and x-ray diffraction (XRD) compositions analysis revealed that the addition of reinforcements and ECAP plastic deformation significantly refined the grain sizes and lead to recrystallization of the Mg matrix. The hybrid particles reinforced Mg matrix showed the dissolutions of secondary phases (β-Mg17Al12) mainly due to the Al2O3 which improves the fracture strain of the composites [5]. The enhanced mechanical properties are resulted from the basic strengthening mechanisms of reinforcements which include the coefficient of thermal expansion (CTE) mismatch, wettability at the matrix and reinforcement interface, and Orowan strengthening. However, the ductility of the single reinforcement reinforced composites was negatively affected after a certain limit of the weight percentages of reinforcement [5,6]. The maximum mechanical properties of the AZ61 hybrid (Al2O3 and SiC) composites were obtained for the two pass ECAP (ECAP-2P) deformation. The maximum hardness, yield strength (YS), ultimate strength (UTS), and elongation were 61.2±4.6 HV, 127.26 MPa, 250.1 MPa, and 19.3% respectively [8]. The enhanced mechanical properties were obtained from the grain refinement, CTE between the matrix and hybrid reinforcements, and higher percentage of crystallinity [5-8]. The fracture surface of the aged AZ61 hybrid composite exhibited more cleavage structure morphology which indicates a brittle behavior. However, ECAP deformation processing led to the formation of more dimple structures in the fracture morphology which confirms the ductility enhancement [8].

Acknowledgments
The authors would like to thank the Ministry of Science and Technology, Republic of China (Taiwan), Contract Number: MOST 109-2224- E-011-002, for their support of this research.

References
[1] B.L. Mordike, T. Ebert, Materials Science and Engineering A 302 (2001) 37–45.
[2] H. Dieringa, Metals 8 (2018).
[3] M. Besterci, K. Sülleiová, O. Velgosová, B. Ballóková, S.J. Huang, High Temperature Materials and Processes, (2016).
[4] K.B. Nie, K.K. Deng, X.J. Wang, T. Wang, K. Wu, Materials Characterization 124 (2017) 14–24.
[5] S. Huang, M. Subramani, C. Chiang, Composites Communications 25 (2021) 100772.
[6] S.-J. Huang, M. Subramani, A.N. Ali, D.B. Alemayehu, J.-N. Aoh, P.-C. Lin, International Journal of Metalcasting 15 (2021) 780–793.
[7] S.J. Huang, A.N. Ali, Journal of Materials Processing Technology 272 (2019) 28–39.
[8] S.J. Huang, M. Subramani., K. Borodianskiy., Materials Today Communications, 31 (2022) 103261.

ON THE DIFFERENT REGIMES OF PHONON TRANSPORT

Huberman S.
McGill University, Quebec, Canada
samuel.huberman@mcgill.ca

Thermal processes are ubiquitous across all scales of space and time. Work done in the last decade has led to a number of experimental and theoretical advances that have enabled scientists and engineers to construct an accurate picture of phonon transport at small length and time scales. We will discuss these advances in the context of a few case studies. Frist, we experimentally and theoretically examine deviations from the diffusive regime of thermal transport in SiGe alloys, thereby extending current theory and experiment to the study of size effects in thermal transport to bulk materials in the transient grating geometry. Additionally, we go beyond the single mode approximation to the Boltzmann transport equation and develop a formalism to study size effects and phonon hydrodynamics by solving the full scattering matrix version of the linearized Boltzmann transport equation. Using this formalism as a guide, we report the experimental observation of second sound in graphite and ballistic transport in silicon.

NONLINEAR DYNAMICS OF A MICROELECTROMECHANICAL RESONATOR IN THE CIRCUITS OF PHASE LOCKED LOOP AND AUTOMATIC GAIN CONTROL SYSTEMS

Igumnova V.S.[1], Indeitsev D.A.[1,2], Kuznetsov N.V.[1,2,3], Lukin L.V.[1], Popov I.A.[1]
1 - Peter the Great St.Petersburg Polytechnic University (SPbPU)
2 - Institute for Problems in Mechanical Engineering of the Russian Academy of Sciences
3 - St Petersburg University
igumnovavs@mail.ru

In this paper, we study various implementations of a phase locked loop system operating in conjunction with an automatic gain control system to control the primary oscillations of micromechanical resonators using an RR-type gyroscope as an example. In order to measure the angular velocity of an object with high accuracy, it is necessary to ensure the stability of the amplitude and frequency of the primary oscillations of the sensitive element. Automatic gain control is necessary to maintain the primary oscillations at the initially set level. The task of the PLL is to maintain the frequency of the voltage-controlled oscillator at a value equal to the resonant frequency of the primary oscillations. The output of the phase detector, which is an integral part of the PLL, is a frequency doubled signal, which results in high frequency oscillations that are undesirable in the control system. To avoid this disadvantage, an alternative implementation of the PLL circuit is proposed, which allows you to remove the double frequency signal at the output of the phase detector and lower the order of the system. This is the main reason for using control systems. In the Simulink software package, a system nonlinear model of a micromechanical gyroscope is assembled, taking into account the control loops of primary oscillations. The output characteristics of control systems are presented, as well as the dynamics of the sensitive element along the primary axis of motion. A comparison of two PLL systems was carried out in terms of such characteristics as: speed, delay area in the operating mode, as well as resistance to changes in the parameters of the control system.

STABILITY OF THE ANEURYSM IN A MEMBRANE TUBE WITH LOCALIZED WALL THINNING FILLED WITH A FLUID WITH A NON-CONSTANT VELOCITY PROFILE

Il'ichev A.T.[1], Shargatov V.A.[2]
1 - Steklov Mathematical institute RAS, Moscow, Russia
2 - National Research Nuclear University MePHI, Moscow, Russia
ilichev@mi-ras.ru

We perform the stability analysis of bulging localized structures on the wall of a fluid-filled axisymmetric membrane elastic tube. The wall of the tube is assumed to be subjected to localized thinning. The problem has no translational invariance any more, hence the stability of a bulging wave centered in the point of the localization of imperfection is essential, and not orbital stability up to a shift as in the case of translationally invariant governing equations. Localized bulging motionless wave solutions of the governing equations are called aneurysm solutions. We assume that the fuid is subjected to the power law for viscous friction of a non-Newtonian fuid, though the viscosity does not play a significant role and it can be neglected. The velocity profile remains not constant along the cross section of the tube (even in the absence of the viscosity), because no-slip boundary conditions are performed on the tube walls. Stability is established by demonstrating the non-existence of the unstable eigenvalues with a positive real part of the linearized problem . This is achieved by constructing the Evans function depending only on the spectral parameter, analytic in the right half of the complex plane $\Omega+$ and which zeroes in $\Omega+$ coincide with the unstable eigenvalues of the problem. The non-existence of the zeroes of the Evans function is performed using the argument principle from the analysis of complex variable. Finally, we discuss the possibility of application of results of the present analysis to the aneurysm formation in damaged human vessels under the action of the internal pressure.

NUMERICAL RESEARCH OF THE MICROEMULSION SEPARATION DYNAMICS UNDER THERMAL CONVECTION CONDITIONS

Iulmukhametova R.R., Musin A.A., Valiullina V.I., Kovaleva L.A.
Bashkir State University, Ufa, Russia
regina.you@mail.ru

The problem of stable water-in-oil emulsions' destruction remains relevant in many industries. Since the amount of accumulated waste depends on the successful separation of emulsions into phases.

In this work, we studied the process of settling drops of a stable microemulsion under thermal convection using mathematical and experimental modeling methods. An experimental study of the natural convection of the emulsion system was carried out in a cell with the possibility of heating and cooling the walls [1]. The mathematical model is built in the one-fluid approximation and includes the momentum conservation equations, the heat conduction equation for the emulsion as one, and the dispersed phase mass conservation equation. The relative velocity between the phases is written under the assumption that the Stokes and Reynolds numbers are small and considering the Rybchinsky-Hadamard formula. To take into account the effect of surfactants, which form a structural-mechanical barrier on the surface of water droplets, the correction is introduced for the effective viscosity of the surface of emulsion droplets. The value of interfacial resistance is given as a power dependence. The stresses arising during interfacial interaction and the dependence of emulsion viscosity on temperature and concentration are given by empirical formulas.

The effect of convective flow regimes on emulsion separation was studied depending on the temperature difference, droplet size, and volumetric water content in the emulsion for different directions of heat flow.

Studies of the growth dynamics of a layer of settled emulsion droplets have shown that for a finely dispersed emulsion, heating the cell from below leads to a slowdown in the process of separation. As the temperature difference increases, the rate of deposition of microemulsion droplets decreases. This is explained by the fact that with an increase in the Rayleigh number, the rate of convective mixing of the liquid increases and some of the emulsion drops are carried away by the liquid flow and don't have time to settle immediately, which leads to some slowdown in the process of emulsion separation, and the ongoing processes of droplet coagulation don't lead to the formation of sufficiently large agglomerates.

The reported study was funded by the grant of the Russian Science Foundation (project №19-11-00298).

References

Valiullina V. I. et al. Experimental study of the stratification of polydisperse emulsions in a cell with heated walls // JOP: Conf. Series. 2021. V. 2057, No. 1. Paper 012041.

BIOMECHANICS AS THE BASIS OF CLINICAL DECISION SUPPORT SYSTEMS IN SURGERY

Ivanov D.V.
Saratov State University, Saratov, Russia
ivanovdv.84@ya.ru

In Russia, for more than 15 years, the incidence of musculoskeletal system pathologies in Russia has ranged from 7.5 to 8.2%. Despite the fact that in the last decade, according to Rosstat, the level of injuries has been steadily decreasing, it remains one of the leading causes of disability and mortality of the population. Degenerative-dystrophic diseases of the musculoskeletal system also often lead to a serious deterioration in the quality of life and disability of the population. Especially noteworthy is such a combined pathology as coxo-vertebral syndrome, which consists in the presence of pathology in the patient in both the lumbosacral segment of the spine and in the hip joint. The danger of this disease is not only in its high incidence (up to 95% of patients with degenerative changes of the hip joint), but also in the fact that doctors experience serious difficulties in diagnosis and treatment.

Cardiovascular diseases are detected in about 13.3-15.2% of the country's population. In 2018, in Russia, mortality from diseases of the circulatory system ranged from 22.9% for women to 32.5% for men. Among the pathologies of the cardiovascular system, there are cerebral vascular aneurysms that occur in 0.3-5% of the population, do not have a special symptomatic picture and lead to extremely severe consequences when ruptured (in half of the cases of rupture lead to death).

The complexity of the diagnosis and complexity of the above diseases, as well as the fact that different treatment options are possible for each of them, poses the task of developing modern quantitative methods and tools for their research in order to select and justify a successful treatment option in each case. One of the modern tools for helping a doctor and evaluating treatment options are preoperative planning systems or clinical decision support systems.

In recent years, interest in the biomechanical stage in the planning of traumatology and orthopedic treatment has not faded. However, at the moment, preoperative planning systems with biomechanical support for choosing the optimal treatment option have not been developed anywhere in the world. Modern medicine does not stand still, and a patient-oriented approach to treatment is the central task of modern healthcare. Methods of obtaining medical data, such as methods of radiation examination, ultrasound (ultrasound) and magnetic resonance examination (MRI), provide doctors with ample opportunities for preoperative diagnosis and treatment planning. These same methods, as well as the

development of fundamental science and computer technology, make it possible to process medical data quickly and accurately, set and solve biomechanics tasks, and implement the results of biomechanical modeling into the routine process of preoperative planning and examination of the patient.
The development and implementation of quantitative methods for assessing the severity of the disease and its treatment options based on biomechanical modeling can significantly improve the quality of treatment, as well as improve the postoperative prognosis and quality of life of patients.
The purpose of this study is to create biomechanical foundations of systems to support clinical decision-making in surgery of the musculoskeletal system and cardiovascular system, and their introduction into routine practice of preoperative diagnosis and planning.

SEISMIC ANALYSIS OF DAM-FOUNDATION SYSTEM WITH FREE-FIELD VISCOELASTIC ABSORBING BOUNDARY

Ivanov P.S.
Vedeneev VNIIG JSC, Saint Petersburg, Russia
ivanovps@pm.me

The most general approach of modeling concrete dam under earthquake load is to consider foundation region large enough to include earthquake source. It allows to model seismic wave propagation to the dam site. Results accuracy is limited by lack of information about such wide region. To overcome such limitation truncated model must be created with boundary conditions that substitute the dropped foundation. Viscous absorbing boundary condition that consists of dashpots is traditionally used for that purpose [1]. Viscoelastic boundary has been proposed by VNIIG experts to overcome issues of viscous boundary with lower frequencies [2]. Additional forces on the boundary should be derived to account for free-field ground motion of truncated part of the foundation [3].
In this report result of different boundary conditions performance comparison is provided. Comparison has been conducted using 2D model of concrete dam on uniform rock foundation implemented in Abaqus. The result shows that free-field motion forces should be considered to sufficiently model the dam-foundation system response under a seismic load.

1. Lysmer, J., & Kuhlemeyer, R. L. (1969). Finite dynamic model for infinite media. Journal of the engineering mechanics division, 95(4), 859-877.
2. Tseytlin, B. V., & Le-Zakharov, S. A. (2020). Boundary Conditions at the Border of the Foundation Area when Calculating Vibrations of Hydraulic Structures. Proceeding of the VNIIG, 295, 78-89.
3. Løkke, A., & Chopra, A. K. (2017). Direct finite element method for nonlinear analysis of semi- unbounded dam–water–foundation rock systems. Earthquake Engineering & Structural Dynamics, 46(8), 1267-1285.

ALGORITHMS FOR FLOW SIMULATION AROUND MOVABLE AIRFOILS IN VORTEX METHODS

Izmailova Yu.A., Marchevsky I.K.
Bauman Moscow State Technical University, Moscow, Russia
yulia.izmailova@mail.ru

Vortex methods of computational fluid dynamics belong to the class of Lagrangian meshless methods for flow simulation. In the framework of vortex methods the primary computational variable is vorticity. The flow around airfoil can be described through vorticity evolution in the flow domain and vorticity generation at the boundary of the streamlined airfoil.
Nowadays, a lot of different modifications of vortex methods are known, but it should be noted that the methods for plane flows simulation are much better developed than three-dimensional ones. In the case of plane flows, the vorticity is a scalar field. This fact allows for constructing a mathematical model taking into account the viscosity influence, while remaining within the framework of the Lagrangian approach to describing the vorticity evolution.
Due to rather low computational complexity, vortex methods are well applicable for a number of actual engineering problems. For example, to simulate essentially unsteady flow regimes around airfoils or airfoil systems. Such airfoils can be both movable and deformable. Often in such problems, it is of interest to calculate the hydrodynamic loads acting on the airfoil. If it is necessary to simulate transient mode, when hydrodynamic loads acting on the airfoil are essentially unsteady, simplified flow models (for example, based on stationary hydrodynamic coefficients or added masses/potential theory) are inapplicable or lead to unacceptably poor accuracy. Due to Lagrangian approach to motion description, the vortex methods are efficient in such problems since computational complexity in case of movable airfoil is just slightly higher against immovable one. In particular, there is no need to reconstruct the mesh in the flow domain at each time step due to its absence, and it is also possible to simulate arbitrarily large displacements and rotations of a streamlined airfoil.
The VM2D code has been developed for two-dimensional incompressible flow simulation. It is based on the viscous vortex domains (VVD) method, as well as some original authors' improvements, mainly related to schemes for numerical solution of the integral equations. This code currently allows for solving a wide class of problems. However, the solution of coupled hydroelastic problems led to a computational instability for "light" airfoils which inertial

properties (mass and moment of inertia) are commensurate with inertial properties for the displaced volume of the medium.
In the present work, a new iterative algorithm for flow simulation around "light" airfoils performing hydroelastic oscillations is implemented. This algorithm is developed according to the coupling scheme and uses the added masses calculation technique. The results are demonstrated for a model problem of wind resonance for the circular airfoil (viscous incompressible flow simulation around a circular cylinder oscillating across the incident flow). The number of iterations depends on masses ratio; the lighter airfoil is the slower convergence rate is observed. The implemented scheme allows for correct simulation of the oscillations frequency in the flow.

MATHEMATICAL MODEL OF NANOINDENTATION IN THE TAPPING MODE ATOMIC FORCE MICROSCOPY IN THE STUDY OF SUBSURFACE STRUCTURES OF FILLED ELASTOMERS

Izyumov R.I., Svistkov A.L.
Institute of Continuous Media Mechanics, Perm, Russia
izumov@icmm.ru

The paper presents the results of developing a mathematical model of the nanoindentation process in the tapping mode atomic force microscopy. The purpose of the work was to substantiate the methodology for constructing the subsurface layer structure of the material under study. The method is suitable for studying soft filled materials. This method consists in constructing a three-dimensional image of a rigid filler structure hiding under the surface using a phase portrait and a relief map of the sample surface.
The model considers the AFM cantilever as a spring pendulum with given parameters (stiffness and resonant frequency) and calculated ones (effective mass and internal viscosity). The parameters of the numerical model describe the real experimental setup. The behavior of the material is described by an elastic model, the dissipation is given by the forces of adhesion that draw the probe into the material after contact with its surface.
For a given material and experimental parameters, the obtained phase shift map is interpreted as the result of the influence of rigid objects located at a certain depth. The values of these depths are converted into the relief of hidden subsurface structures.
The reported study was funded by RFBR and Perm Territory, project number 20-41-590001 and the Ministry of Science and Higher Education of the Russian Federation (theme No. AAAA- A20-120022590044-7).

COMPUTATIONAL ASPECTS OF CLOSING THE GAP BETWEEN MECHANICS AND MATERIALS SCIENCE

Kachanov M.[1,2,3]
1 - Tufts University, Medford, USA
2 - Nizhny Novgorod State University named after Lobachevsky, Russia
3 - Saint Petersburg State Polytechnic University named after Peter the Great, Russia
mark.kachanov@tufts.edu

In the mechanics of composites – and, more generally – of heterogeneous materials, quantitative modeling of their effective properties (such as the elastic and the conductive ones) focuses on inhomogeneities of the *ellipsoidal* shapes. For example, in case of cracks, the latter are assumed to be penny-shaped), pores are usually assumed to be spherical or, at most, spheroidal. Then, classical results of the Eshelby theory can be utilized, and the existing effective media theories focus on the effects of interactions. However, inhomogeneities in most materials (ceramics, geo-materials, metals) have highly "irregular" shapes. The shape factor usually plays a dominant role, as compared to the effect of interactions, for example it manifests itself, rather strongly, even in the non-interaction approximation.
The question arises, of quantitative characterization of "irregular" microgeometries and on extending the effective media theories to them. This challenge can be rephrased as bridging the gap between mechanics (quantitative methods) and materials science (largely observational). The present lecture reviews the progress that has been achieved in this direction and outlines challenges for the computational studies that, in our opinion, should be addressed.
References
1. Kachanov, M. and Sevostianov, I. (2018) Micromechanics of Materials, with Applications. Springer, 712p. https://doi.org/10.1007/978-3-319-76204-3
2. Zohdi, T. and Wriggers, P. (2010) Introduction to Computational Micromechanics. Springer.
3. Martynyuk, M. and Kachanov, M. (2020) Elastic compliances and stress intensity factors of multilink zig-zag cracks, *International Journal of Engineering Science* **148**, 103225. https://doi.org/10.1016/j.ijengsci.2020.103225
4. Sevostianov, I. and Kachanov, M. (2008) On approximate symmetries of the elastic properties and elliptic orthotropy, *International Journal of Engineering Science* **46**, 211-223.
5. Zimmerman, R. W. (1986) Compressibility of two-dimensional cavities of various shapes. *ASME Journal of Applied Mechanics* **53**, 500-504.
6. Sevostianov, I. and Kachanov, M. (2012) Is the concept of "average shape" for a mixture of inclusions of diverse shapes legitimate? *Intern. Journal of Solids and Struct.* **49,** 3242-3254

MECHANICAL PROPERTIES PREDICTION OF COMPOSITE MATERIALS USING DATA-DRIVEN MODELS WITH PERIODICITY RECONSTRUCTION

Karamov R.[1,2], Lomov S.V.[1,2], Sergeichev I.[1], Swolfs Y.[2], Akhatov I.[1]
1 - Skoltech, Moscow, Russia
2 - KU Leuven, Leuven, Belgium
radmir.karamov@skoltech.ru

Prediction of mechanical properties of advanced structural materials is one of the high-demanded topics in the industry. Recently, the creation of so-called "digital twins" has gained popularity in the literature, which are represented as mathematical prediction models based on real data for numerical calculations of heterogeneous materials' mechanical properties. However, these digital twins require new approaches compared with theoretical models with ideal geometries. For instance, the application of periodic boundary conditions on a data-driven representative volume element (RVE) is not trivial. If the geometry of the RVE on the opposed faces differs (RVE is not periodic), then structural inconsistencies near the boundaries introduce artificial stress and strain fluctuations, which influence the calculation results. These problems are especially relevant for representative volume elements obtained with micro-computed tomography (micro-CT), where full periodicity cannot be achieved due to the nature of the materials. We propose reducing boundary artificial stress and strain fluctuations by enlarging a three-dimensional image so that the reconstructed volume element is quasi-periodic, using inpainting [1] and super-resolution techniques based on deep learning. A generative adversarial network (GAN) with custom periodic convolutions was developed to reconstruct periodic structures around the initial RVE. To test the proposed methodology, three-dimensional high-resolution micro-CT images of a random glass fibre composite were used: the images were enlarged, so they have a periodic structure. Finite element models of RVEs from both original and enlarged micro-CT images were created, with identification of local fibre orientation using a structure tensor analysis [2] (VoxTex software). The RVE periodic modification leads to a more accurate prediction of material stiffness, eliminating the stress boundary artifacts in the initial RVE.

References

[1]. Karamov, R., Lomov, S. V., Sergeichev, I., Swolfs, Y., & Akhatov, I. (2021). Inpainting micro-CT images of fibrous materials using deep learning. Computational Materials Science, 197, 110551. https://doi.org/10.1016/j.commatsci.2021.110551

[2]. Straumit, I., Lomov, S. V., & Wevers, M. (2015). Quantification of the internal structure and automatic generation of voxel models of textile composites from X-ray computed tomography data. Composites Part A: Applied Science and Manufacturing, 69, 150–158. https://doi.org/10.1016/j.compositesa.2014.11.016

DETERMINATION OF PARAMETERS OF A MODEL OF MECHANICAL PROPERTIES OF HIGH PERMEABILITY RESERVOIRS OF GAS FIELDS

Karev V.I.
Institute for Problems in Mechanics RAS, Moscow, Russia
wikarev@ipmnet.ru

It is necessary to determine the adequate values of the model parameters for mathematical modeling of processes in reservoirs of oil and gas fields. Such opportunity is provided by tests on a true triaxial loading facility, which allows to recreate on samples of the studied rocks under laboratory conditions real stress-strain states occur in the formation in the course of technical-technological operations on wells. The work is devoted to the determination of the parameters of mathematical models and their features for the rocks of highly permeable reservoirs of gas and gas condensate fields on the Triaxial Independent Loading Test System of the IPMech RAS.

The rocks of the Cenomanian horizon of the PK1 formation of the gas and gas condensate fields of the Arctic shelf of Russia were studied. The core material was a highly permeable, highly porous sandstone with a weakly expressed bedding structure.

Three types of tests were carried out: the so-called triaxial tests, the simulations of the stress-strain state on the walls of a horizontal well, and tests according to the "hollow cylinder" scheme, i.e. all-around loading samples with a central hole along one of the axes.

During triaxial tests, three cycles of uniaxial loading were carried out at different levels of all-around compression. Samples cut at an angle of 0, 45, 90 degrees to the bedding plane were tested. These experiments made it possible to determine the elastic and strength characteristics of the studied rocks.

In the course of the second type of tests, a pressure at the bottom of the well was determined, at which destruction began at a certain point on the contour of the horizontal well. The samples were cut and loaded so that the angle between the maximum compressive stress and the normal to the bedding plane was 0, 30, 45, and 90 degrees for various samples (which corresponded to the stress states at the points of the contour of the horizontal well, which were off the vertical axis by the corresponding angle).

The third type of tests was a direct modeling of breakouts on walls in wells. When gradual loading of the sample, an air flow was passed through the hole in the sample, and the mass of the carried out sand formed during the destruction of the walls of the hole was recorded. Loading was carried out according to one of three options. In the first variant, the same load was applied on all three axes. The second option was reproducing conditions close to the plane deformation: the samples were loaded, as in the previous version, to stresses approximately corresponding to the rock pressure, then the stresses on the faces parallel to the hole axis increased, the stresses on the faces which oriented perpendicular to the hole axis remained constant . The third option corresponded to the conditions of a plane stress state: the load was applied to the side faces of a sample, and the face with the hole remained free, which made it possible to video record the process of breakout formation.

Thus, in the course of the conducted research, the elastic and strength parameters of the studied rocks, the values of the maximum allowable drawdowns at the bottom of the well, the nature of the formation of breakouts on walls of the well during the increase in loading were determined. The phenomenon of atypical strength anisotropy of the studied rocks is revealed, which consists in a monotonous change in strength with a change in the angle between the direction of action of maximum compressive stresses and the plane of occurrence. Although it is usually considered for rocks that the lowest strength corresponds to points located at an angle of about 30 degrees (depending on the angle of friction), where shear stresses are maximum along the weakening planes. This is a new phenomenon that requires a theoretical explanation.

MATHEMATICAL MODEL OF AUTOCRINE REGULATION OF OSTEOCLASTS IN BONE REMODELING

Karimov A.I.[1,2], Mustafina S.I.[1,2], Kireev V.N.[1,2], Solnyshkina O.A.[1,2], Bilyalov A.R.[2], Chugunov S.S.[3], Pavlov V.N.[2], Akhatov I.Sh.[3]

1 - Bashkir State University, Ufa, Russia

2 - Bashkir State Medical University, Ufa, Russia

3 - Skolkovo Institute of Science and Technology, Moscow, Russia

aidar.karimov2015@yandex.ru

Bone tissue remodeling is a continuous biological process occurring on an ongoing basis in various discrete areas of the skeleton. The process is characterized by a stage of resorption of existing mineralized tissue by osteoclasts and a stage of subsequent formation of new bone tissue by osteoblasts. Bone remodeling disorders are seen in diseases such as osteoporosis and Paget's disease. Bone remodeling is a coordinated process involving a group of bone cells (osteoblasts and osteoclasts) working in a structure known as the basic multicellular unit (BMI). Upon initiation of remodeling, osteoclasts differentiate from their monocytic precursors and resorb bone. Later, the process of osteoblast differentiation from mesenchymal precursors is initiated to form new bone tissue. In healthy people under 30 years of age, osteoblasts form the same amount of bone that was resorbed by osteoclasts. This allows you to complete the full cycle of remodeling. In people at a later age, this balance is disturbed.

The progression of bone remodeling at each local site is regulated by numerous autocrine and paracrine factors. Transforming growth factor (TGF β) increases bone formation through a direct effect on osteoblast synthesis. The membrane protein RANKL and osteoprotegerin (OPG) are among the main regulators of bone resorption. They are synthesized by osteoblasts and have the opposite effect on osteoclasts. The regulation of bone remodeling is complex and includes the simultaneous action of a number of factors that affect the formation and/or resorption of bone.

Mathematical modeling provides an important scientific approach for integrating existing knowledge about the regulation of bone cell interactions, as well as for predicting the balance between bone formation and its subsequent resorption [1-2]. In the present study, a mathematical model was built that describes changes in the populations of osteoblasts and osteoclasts and subsequent quantitative changes in bone mass in the local area of bone remodeling. It has been suggested that cells interact with each other via effectors that are both autocrine and paracrine.

It was found that the system can exist in two stable modes: a single cycle of remodeling in response to an external stimulus, and a series of internal cycles of bone remodeling. These two modes correspond to targeted and random bone remodeling, respectively. It was found that the nature of the dynamic behavior of the system depends mainly on the parameter reflecting the autocrine regulation of osteoclasts.

The study was carried out within the framework of a grant from the Republic of Bashkortostan for state support of scientific research conducted under the guidance of leading scientists.

References

1. Komarova S.V., Smith R.J., Dixon S.J., Sims S.M., Wahl L.M. Mathematical model predicts a critical role for osteoclast autocrine regulation in the control of bone remodeling // Bone. 2003. Vol. 33, No. 2. P. 206-215.

2. Lemaire V., Tobin F.L., Greller L.D., Cho C.R., Suva L.J. Modeling the interactions between osteoblast and osteoclast activities in bone remodeling // Journal of theoretical biology. 2004. Vol. 229, No. 3. P. 293-309.

OSCILLATORY DYNAMICS OF LIQUID-LIQUID INTERFACE IN RADIAL HELE–SHAW CELL

Karpunin I.E.[1], Kozlov N.V.[2], Kozlov V.G.[1]
1 - Laboratory of Vibrational Hydromechanics, Perm State Humanitarian-Pedagogical University, Perm, 614990, Russian Federation
2 - Laboratory of Hydrodynamic Stability, Institute of Continuous Media Mechanics UrB RAS, Perm, 614013, Russian Federation
karpunin_ie@pspu.ru

The dynamics and stability of the interface between two immiscible liquids of close densities and different viscosities are investigated in a radial Hele-Shaw cell. Radial displacement of a more viscous liquid by a low-viscosity liquid and leveling of the interface with a developed Saffman–Taylor instability are considered. The effect of the harmonic change in the fluid flowrate on the stability of the interface of immiscible liquids, depending on the thickness of the working layer, the relative position of low-viscosity and viscous liquids in the cuvette, as well as with varying characteristics of liquids, has been experimentally investigated. The cell, it is a plane radial layer, organized by two glass discs. In the center of one of the glasses, there is an opening for feeding a displacing liquid into the layer filled with another liquid. The working liquids are selected in such a way that their densities are close, and their viscosity differs by several orders of magnitude.

At small amplitude of oscillations and in the absence of an average pumping, the interface performs radial oscillations in all the cases considered. In this case, in the phases of maximum compression and maximum expansion, the interface is strictly concentric relative to its center. With an increase in the amplitude of the oscillations, when a sufficient displacement rate is reached, instability is formed at the interface in a threshold manner. At the interface between liquids, instability of the type of "viscous" fingers is formed – a low-viscosity liquid locally breaks into a layer of a more viscous liquid. The threshold for the onset of instability is determined by the amplitude of the oscillation of the interface. When instability occurs, the distance from the liquid interface to the center of the cavity is also decisive, since in the radial formulation the velocity is the greater, the closer to the center. Comparison of experimental data suggests that at the interface a quasi-stationary instability of the Saffman–Taylor type is formed. The results obtained in experiments on layers of different thicknesses, in the inverted case and in the case of variation in the relative viscosity, indicate that the characteristic value of the range of boundary oscillations at the onset of finger instability is determined by the dimensionless frequency. That parameter depends on the oscillation frequency, layer thickness, and viscosity of a low-viscosity liquid. The dimensionless frequency characterizes the ratio of the channel width to the thickness of the Stokes layer. In the limit of high dimensionless frequencies, the fluid performs inviscid oscillations, and the dependence of processes, including stability, on frequency should be absent. With a decrease in the value of the dimensionless frequency, an increase in the threshold value of the range of oscillations of the boundary corresponding to the onset of instability is observed.

This work was financially supported by the Government of Perm Region and the Russian Foundation for Basic Research (Grant No. 20-41-596011).

STABILITY LOSS OF AN ISOTROPIC PLATE WITH AN ELLIPTICAL INCLUSION UNDER TENSION

Kashtanova S.V.[1], Rzhonsnitskiy A.V.[2]
1 - Institute for Problems in Mechanical Engineering of the Russian Academy of Sciences, Saint-Petersburg, Russia
2 - Saint-Petersburg State Institute of Technology, Saint-Petersburg, Russia
kastasya@yandex.ru

In this presentation, the problem of the stability of an infinite isotropic plate with an elliptical inclusion under uniaxial tension is studied. It occurs since compressive stresses appear, which, at a certain level of tension, lead to the loss of stability of the flat form of equilibrium of the plate. The proposed type of deflection and coordinate system allows one to take the energy integrals analytically, which greatly helps in the implementation of the Ritz method. The aim of the study is to obtain the critical values of the loads at which the plate bulges from a flat shape at different ratios of the Young's modulus of the plate and the inclusion.

To solve this problem, it is necessary to compile the potential energy and operation of the plate and inclusion, which requires formulas for stress fields. One of the first solutions to the problem of stresses with elliptical inclusion belongs to Hardiman, the development continued in Eshelby, then many scientists returned to this question, but in this work the authors use the approach proposed by Malkov. In their work, an exact analytical solution was obtained without decompositions of the desired potentials by degrees, complex functions are solutions to boundary value problems and are fully defined, i.e. they do not contain unknown constants, while in Hardiman formulas there are seven unknown constants.

The scheme of approach to solving problems by the energy method is well known, but the difficulty lies in overcoming computational difficulties, and the use of analytics, which will be discussed in the presentation, greatly simplifies the process.

Funding: The reported study was funded by RFBR, project number 19-31-60008.

NUMERICAL SIMULATION OF GAS AND WATER FILTRATION IN MICROMODELS OF POROUS MEDIUM

Kazina L.Z.[1,2], Nitsenko V.A.[2], Mirzayanov A.A.[1,2], Pityuk Y.A.[1,2], Lomuhin A.Y.[3]
1 - Bashkir State University, Ufa, Russia
2 - RN-BashNIPIneft LLC, Ufa, Russia
3 - JSC Rospan International, Noviy Urengoy, Russia
lz_kazina@bnipi.rosneft.ru

It is necessary to understand the behavior of multiphase system on a pore scale to select and justify the effective composition for limiting water influx in gas wells. Capillary forces depend on interfacial tension and wettability. In the work we used methods of computational microfluidics using OpenFOAM software to analyze the influence of rock wettability on features of multiphase flow in different micromodel of porous medium. We chose mathematical model which allows describing the fluid flow in separate pores and channels by Navier-Stokes equation and the flow in porous medium element using Darcy equation.
In the present work we considered 3 models: T-shaped model, porous doublet and a model with a trapping fracture. The series of calculations for hydrophobic and hydrophilic surfaces were carried out. In the T-shaped model in the case of a hydrophobic surface gas moves predominantly along the fracture with little penetration into porous medium and displacement of water drops that move along the fracture. In the case of a hydrophilic surface part of the gas is filtered into porous medium, and the fracture is pinched by hydrophilic water drops, which leads to gas movement through a porous medium. In the case of a hydrophobic surface most of the water stays in the «pocket» of porous matrix with little penetration into porous medium which indicates the effectiveness of limiting water influx.
In the porous doublet model and model with a fracture we carried out the series of calculations for different flow regimes. Flow rate decreasing leads to increase in volume of residual water in a narrow channel and model traps.
Thus, changing the surface wettability with different displacement agents leads to change of behavior of gas and water filtration along a fracture and a porous medium. Numerical simulation results can be used to select the effective agent for limiting water influx in gas wells.

NUMERICAL RESEARCH ON THE DEPENDENCY OF THE LEFT VENTRICLE PUMPING FUNCTION ON THE MIOCARDIUM CONDUCTIVITY AND THE HEART RATE

Khabibullina A.R., Syomin F.A., Tsaturyan A.K.
Institute of Mechanics Lomonosov Moscow State University, Moscow
khabibullina14@mail.ru

The study presents an axisymmetric model of the left ventricle (LV) of the heart in the circulatory system. The LV was approximated by a body of rotation, and the properties of the material of the ventricular wall were described by a new electromechanical model of the myocardium. Atria, the right ventricle, and the blood vessels of the systemic and pulmonary circulation were represented by a lumped parameter model. The active mechanical stresses in the models depend on biochemical parameters described by the system of ordinary differential equations. Myocardial electrophysiology is described by a simple model with two variables. Despite the simplifications, the model correctly reproduces the dynamics of electrical excitation and mechanical contraction of the myocardium in various scenarios, including the dependence of the developed force on time between adjacent electrical stimuli allowing one to simulate correctly variations of stress and strain of the LV wall in response to a change its conductivity or stimulation frequency.
The major variables of the system hemodynamics were calculated under various scenarios: at rest; during physical activity modeled by increasing the heart rate from 60 to 120 beats per minute and reducing the peripheral blood resistance in the systemic circulation; at atrioventricular blockade, simulated by a skip of one ventricular contraction per four atrial contractions, and acute myocardial infarction of the LVs apex.
The results demonstrate a significant increase in the LV contractility with an increase in heart beat rate as well as the ability of the LV to partially compensate loss of blood flow and arterial pressure in the case of an atrioventricular blockade due to an increase in ventricular contractility in the contraction following the missed one. The results also indicate that a decrease in the LV apex conductance in the case of apical infarction decreases the LV performance. All results correspond to empirical data.
The research was supported by RSF grant 20-74-00046.

EQUATION OF STATE FOR TUNGSTEN AT HIGH PRESSURES AND TEMPERATURES BEHIND THE FRONT OF SHOCK WAVES

Khishchenko K.V.[1,2,3,4]
1 - Joint Institute for High Temperatures RAS, Moscow, Russia
2 - Moscow Institute of Physics and Technology, Dolgoprudny, Russia
3 - Institute of Problems of Chemical Physics RAS, Chernogolovka, Russia
4 - South Ural State University, Chelyabinsk, Russia
konst@ihed.ras.ru

Knowledge of models of thermodynamic properties of various materials in a wide range of pressures and temperatures is required to create adequate numerical models of processes under intense mechanical loads. In the present work, a semiempirical model of the thermodynamic potential of solid and liquid phases of tungsten at high pressures and temperatures is developed. The model is based on the quasi-harmonic approximation for condensed phases and has the ideal gas asymptotics at extremely high densities, temperatures, and specific volumes. The results of calculations of crystal–liquid and liquid–gas phase equilibrium curves, isotherms, and shock adiabats for samples of this metal with different initial density are presented in comparison with the available data from shock-wave experiments. The developed model can be used in numerical simulation of physical processes in matter at high energy densities. This work is done under the support from the Russian Science Foundation (grant No. 19-19-00713, https://rscf.ru/project/19-19-00713/).

MISFIT STRESS IN CORE-SHELL NANOWIRES WITH DIFFUSE INTERFACE

Khramov A.S., Krasnitckii S.A., Smirnov A.M., Gutkin M.Yu.
ITMO University, St. Petersburg, Russia
andrey.khramow@gmail.com

Heterostructures containing diffuse interfaces demonstrate enhanced structural stability to the lattice mismatch relaxation through misfit defect formation despite the deterioration of electro-optical performance of the devices based on these structures [1,2]. Therefore, the investigation of the stress-strain state induced by diffuse interfaces [3] is of a great concern to determine the critical conditions for the onset of relaxation processes in these heterostructures [4,5].
This report aims at providing an elastic model of core-shell nanowires with diffuse interface. The thermoelastic analogy is employed to obtain the misfit stress tensor, the elastic dilatation and the misfit strain energy. The eigenstrain induced by the diffuse interface is described by the Fermi-Dirac step function. The dependence of the misfit strain energy of a core-shell nanowire on the shape factor of the eigenstrain profile is shown and discussed in detail.
This work was supported by the Russian Science Foundation (grant No. 19-19-00617).

References

1. V. Zannier et al., Nano Lett. 18 (2018) 167.
2. D.V. Beznasyuk et al., Phys. Rev. Maters. 4 (2020) 074607.
3. A.E. Romanov et al., Scripta Mater. 176 (2020) 42.
4. J. Svoboda et al., Philos. Mag. Lett. 85 (2005) 473.
5. A.L. Kolesnikova et al., Mater. Phys. Mech. 47 (2021) 697.

ON THE EFFECT OF THE CENTRAL BODY SMALL DEFORMATIONS ON ITS SATELLITE TRAJECTORY IN THE PROBLEM OF THE TWO-BODY GRAVITATIONAL INTERACTION

Kiryan D.G., Kiryan G.V.
Institute of Problems of Mechanical Engineering of RAS, St.Petersburg, Russia
diki.ipme@gmail.com

Analysis of the influence of nonsphericity of a massive central body upon its satellite trajectory is a well-known problem of satellite-based gravity prospecting. However, it has not been yet set out with respect to the Sun and Mercury, and, thus, is of a specific interest. The point of interest is to try, in terms of the classical mechanics, to discover the nature of the so-called ”anomalous” shift of the Mercury's perihelion.
The Mercury's perihelion ”anomalous” shift was found out as a result of many-year diligent work of French astronomer *Urbain Jean Joseph Le Verrier* who observed the Mercury at the Paris Observatory during almost half a century and elaborated the theory of its motion taking into account all the gravitational perturbations he knew at that time. *Le Verrier* revealed that the calculated Mercury's trajectory was somewhat different from the optical observations, namely, the perihelion was being displaced faster than predicted by his theory. The obtained discrepancy appeared to be $\Delta\psi \approx 0.1''$ for the Mercury synodic period. Unfortunately, the classical mechanics has ”almost officially” refused further investigation of the $\Delta\psi$ nature.
The performed study of the eFFect of the Sun's nonsphericity on the Mercury's trajectory has shown that the so-called

”anomalous” shift of the Mercury’s perihelion, that is, the angular discrepancy, is a result of the fact that *Le Verrier* assumed in his calculations that the Sun is a material point.
The practice of satellite-based gravity prospecting of the Earth, Moon shows that the artificial satellite trajectory is quite sensitive to gravity anomalies of the central body. In our case, the role of the satellite indicating the Sun’s gravity anomalies is played by Mercury. The real indicator of the Sun’s gravity anomaly is the Mercury’s angular discrepancy $\Delta\psi \approx 0.1''$. The fact that Mercury in its motion is sensitive to the Sun’s gravity anomalies makes it clear to us that, if peculiar features of the Sun deformation are taken into account in the theoretical model of Mercury’s motion, then the ”anomalous” shift detected by *Urbain Le Verrier* merely disappears. Actually, the problem of interpretation of ”anomalous” shift $\Delta\psi$ reduces to the inverse satellite-based gravity prospecting problem as applied to the Sun and its satellite Mercury.

STUDY OF THE ULTRASONIC FIELD DISTRIBUTION USING A THERMOCOUPLE

Klimova A.K., Lukin A.Ya., Andreeva T.A., Konev D.V.
Peter the Great St.Petersburg Polytechnic University, St.Petersburg, Russia
sashkaklimova1997@gmail.com

Over the past decades, high-intensity focused ultrasound (HIFU) has become widely used for non-invasive treatment of neoplasms of various localization. Temperature control during HIFU therapy is important to minimize adverse effects. To study HIFU heating, a stand with thermocouples was used. When a thermocouple is exposed to ultrasound, several effects are recorded that are not described by a simple model of medium heating by ultrasound with a known intensity distribution and heat propagation by thermal conduction. During sonication, a relatively rapid rise in temperature first occurs, followed by an almost linear increase. After the termination of exposure, a rapid drop in temperature is observed, followed by a slow decrease in temperature to the initial value. An analysis of the measurement results showed that this effect is associated with processes at the thermocouple-medium interface. A systematic study of the heating of a thermocouple due to heat release in the boundary layer was carried out. It is shown that in a wide range of exposure duration and ultrasound intensity, the heating of a thermocouple because of effects near its surface depends almost linearly on the amplitude of the sound wave, and not on its intensity. The good reproducibility of the effect opens the possibility of using the thermocouple as an inexpensive alternative to the hydrophone for measuring ultrasound parameters and checking the parameters of HIFU devices, which is especially important for the medical application of HIFU therapy.

A TWO-LEVEL APPROACH TO DESCRIBING THE PROCESS OF COMPOSITE SYNTHESIS

Knyazeva A.G.
ISPMS SB RAS
anna-knyazeva@mail.ru

Establishing the correlation between the processes occurring during the synthesis of a new material at different scale levels, including the formation of equilibrium and nonequilibrium chemical compounds and phases, structure features, formation of accompanying and residual stresses and deformations that change the ways of physical and chemical stages, is important for elucidating the mechanisms of structure and property formation. In general, the relation between mechanics and thermodynamics as applied to the description of processes of irreversible deformation of the medium and physicochemical transformations in it has long attracted the attention of researchers. Consideration of nonlinear rheological laws, dependence of properties on temperature and composition leads to complication of the mathematical description, appearance of new concepts and directions, including tensor chemical potential, nano-thermodynamics, and multilevel models. However, numerous works, as a rule, do not pay attention to the fact that the internal relations between different phenomena in liquid and solid media are much richer than it is accepted in classical approaches.
In this paper we propose an approach to the solution of this problem on the example of modeling the synthesis process of composite under laser and electron-beam alloying of powders Ti and Al with additives of elements forming the strengthening phase in situ. The mathematical and computational problems arising in this case require a special discussion. It is the correctly formulated coupled models and suitable computational algorithms that take into account the relations between the physical and geometrical scales that will reveal the ways to control the corresponding technologies.
Note that the stages of reactions under conditions of synthesis of composites have been analyzed only for model systems and within the framework of works with the allocation of the so-called reaction cells, where the sequence of stages was set in accordance with the equilibrium state diagrams. Despite the considerable success of such studies, the use of reaction cells raises many questions for nonequilibrium conditions accompanied by complex stress-strain states and the complex nature of motion control in 3D technologies. An alternative to such a simplified approach could be the transition to explicitly two-level models that take into account the natural difference in the scales of different physical and chemical processes.
Three variants of such models are possible, differing in the way of describing the stages of reactions (both physical and chemical stages are meant). Among them: (a) the method based on the selection of an equivalent mesocell with

movable boundaries between phases of different composition (similar to the known models in macrokinetics); (b) the method based on the application of the phase field method; (c) the method based on the ideas of mechanics of heterogeneous media with introduction of exchange coefficients (parameters) between phases.
The research was carried out at the expense of the Russian Science Foundation grant No 22-11-00100, https://rscf.ru/project/22-11-00100/

PENETRATIVE CONVECTION IN N-LAYERED POROUS MEDIUM WITH THIN AIR INTERLAYERS AND INTERNAL HEAT SOURCE

Kolchanova E.A., Kolchanov N.V.
Perm State University, Perm, Russia
kolchanovaea@gmail.com

We study the onset of penetrative convection via internal heating in a multilayered heat-generating porous medium with thin air interlayers under the gravitational field. The system is bounded with impermeable plates of equal temperature at the top and bottom. The penetrative convection occurs due to internal heat source placed into each of the porous sublayers. The heat source strength is proportional to the solid fraction. The convective flow of a particular wavelength initiates inside the upper unstably stratified region and penetrates into the lower stably stratified one. The onset value and wave number of critical roll flows are calculated by the shooting method. The case of the thin air sublayers sandwiched between the porous sublayers is considered. It allows reducing the multilayered system with the alternant air and porous sublayers to a system of porous sublayers only but with effective boundary conditions. The additional parameters, namely, an interlayer parameter ε and a parameter ζ of the difference between air and porous thermal conductivities appear. The problem is new and generalizes previous studies [1–3] to an N-layered partially-filled porous medium.
It has been shown that the large-scale convection which covers the entire half of the system where the air is unstably stratified can only arise in the N-layered medium with the porous sublayers of equal permeability, depth, solid fraction, and thermal conductivity. The onset of such a convective flow speeds up and the critical wave number mainly decreases with increasing an air interlayer depth and a difference between the air and porous thermal conductivities. The effect becomes more pronounced with increasing a number of porous sublayers and so a number of air interlayers. The air interlayers destabilizes the motionless state effectively. The localization of convection is possible in the upper highly permeable porous sublayer which is included in the system with the porous sublayers of distinct permeability.
The work was supported by the Russian Science Foundation (Grant No. 21-71-10045), https://rscf.ru/en/project/21-71-10045/.

References
[1]. Kuznetsov, A.V., Nield, D.A.: The effect of vertical throughflow on the onset of convection induced by internal heating in a layered porous medium. Transport in Porous Media. 100 (1), 101-114 (2013) https://doi.org/10.1007/s11242-013-0207-1
[2]. Shalbaf, S., Noghrehabadi, A., Assari, M.R., Dezfuli, A.D.: Linear stability of natural convection in a multilayer system of fluid and porous layers with internal heat sources. Acta Mechanica 224, 1103-1114 (2013) https://doi.org/10.1007/s00707-012-0793-y
[3]. Kolchanova E., Kolchanov N.: Onset of internal convection in superposed air-porous layer with heat source depending on solid volume fraction: influence of different modeling. Acta Mechanica. 233, 1769-1788 (2022) https://doi.org/10.1007/s00707-022-03204-8

ONSET OF CONVECTION IN TWO-LAYERED SORBING POROUS MEDIUM WITH CLOGGING UNDER NON-ISOTHERMAL CONDITIONS

Kolchanova E.A., Kolchanov N.V.
Institute of Continuous Media Mechanics UB RAS, Perm, Russia
kolchanovn@gmail.com

We continue and expand the previous study of [1] by considering double-diffusive convective instabilities in a two-layered porous medium saturated with the mixture made up of a carrier fluid and solid nanoparticles. The latter ones are considered as solute particles. The two horizontal porous sublayers have distinct permeabilities. They are allowed to be heated either from above or from below in the presence of the gravitational field. A maximal solute concentration is at the upper boundary of the layered porous medium but zero concentration is set at the opposite lower boundary. One gets favorable conditions for the excitation of thermosolutal (double-diffusive) convection over the solutal and thermal profiles in the medium.
One considers the anisotropic porous medium as a reactive system, which can absorb nanoparticles. So, mixture transport is accompanied by the immobilization of solute particles. This process is described by the mobile/immobile media model, which takes into account the nonlinear kinetic equation for mixture redistribution between the mobile (moving with the carrier fluid) and immobile (sticking to the porous matrix) phases. The equations for convective flows

in each of the porous sublayers are written within the Boussinesq approximation. The equations are solved numerically by the shooting method.
The clogging effect on the onset of thermosolutal convection has been investigated under the non-isothermal conditions. The bimodal marginal stability curves are plotted at different fixed values of the buoyancy ratio. This ratio includes the variations of mixture density due to thermal and solutal differences across the layered porous system. Stability maps for the system with the upper highly permeable sublayer are also given at different values of permeability ratios and different positions of the sublayer interface. It has been shown that the onset value of double-diffusive convection decreases with the growth of positive buoyancy ratio (heating of the system from below) but it, on the contrary, increases with that of the absolute negative buoyancy ratios (heating from above). It is possible due to the fact that in the first case both density gradients caused by the thermal and solutal differences are directed upwards so that a heavy cold solute accumulates near the upper boundary of the porous system and induces the most effective unstable density stratification. In the second case, the thermal and concentration density gradients are directed oppositely to each other, so the mixture motionless state stabilizes with the growth of temperature difference at the external boundaries of the layered medium. The clogging effect both under the isothermal and non-isothermal conditions can change the scale of convective roller flow abruptly: from the local convection to large-scale convection. This situation is typical for all of the heating directions (from below or from above).
The work was supported by the Russian Science Foundation (Grant No. 20-11-20125).

References
1. Kolchanova, E.A., Kolchanov, N.V.: Onset of solutal convection in layered sorbing porous media with clogging. International Journal of Heat and Mass Transfer. 183 (A), 122110 (2022) https://doi.org/10.1016/j.ijheatmasstransfer.2021.122110

VERIFICATION OF THE ALGORITHMS OF VORTEX METHODS IN THE VM2D CODE FOR 2D FLOWS SIMULATION

Kolganova A.O., Marchevsky I.K.
Bauman Moscow State Technical University, Moscow, Russia
kolganchik@gmail.com

Meshless Lagrangian vortex particle methods are widely used in engineering applications; they are usually considered as an efficient tool for hydrodynamics loads estimating, which act the structure in the flow. Key advantages of vortex particle methods are connected with rather low computational complexity of the algorithm, exact satisfaction of the perturbation decay boundary condition on infinity at external flows simulation and the possibility to simulate unsteady regimes in coupled fluid-structure interaction problems.
Well-known, rather old versions of vortex methods are based on the potential theory. The simplest possible flow model is used in them - inviscid incompressible media. Thus, it is possible to apply them correctly only to the narrow class of problems where viscous effects are not essential and can be neglected.
Modern modifications of vortex methods allow for correct simulations of viscous flows in 2D problems; the Viscous Vortex Domains method is implemented in the VM2D code together with original numerical schemes and algorithms. The code is open-source, cross-platform and freely available in Github repository; parallel computational technologies OpenMP, MPI and Nvidia CUDA are supported.
The main aim of the present research is validation of the VM2D code on known model problems and estimating the required discretization for correct simulation of viscous flows. Number of model problems is considered, such as classical exact solutions of the Navier - Stokes equations (the Poiseuille and the Couette flows, the Blasius boundary layer near thin plate), flow around circular cylinder at low and intermediate values of the Reynolds number, flow around system of airfoils, flow around the rectangular airfoil with elongation from 3.0 to 10.0. Both steady (averaged over large time period) and unsteady flow characteristics are computed; they are in good agreement with experimental data and known results of numerical simulation.
The actual problems are outlined which solution is required for further improvement of the vortex particle method algorithms, both for computational complexity improvement and widening of the range of the problems for simulation.

ADVANCED SYSTEM FOR MULTIDISCIPLINARY NUMERICAL STRENGTH AND WEIGHT ANALYSIS OF CIVIL AIRCRAFT STRUCTURES AT PRELIMINARY STAGES OF DESIGN

Shanygin A.N., Kondakov I.O., Vedernikov D.V., Guseva N.V., Chernov A.V.
Central Aerohydrodynamic Institute (TsAGI)
ivan.kondakov@tsagi.ru

One of the key tasks of preliminary stages of civil aircraft design is to define basic parameters of aircraft structure geometry. This task requires significant labor input, as the search of optimal zones of structure parameters if performed. In order to decrease the labor, approximate methods and simplified models are used, that lead to considerable errors in calculations, which have to be refined at a later stages.

The presented system of numerical strength analysis of civil aircraft structures is a fully automated algorithm of aircraft design, capable of searching optimal external geometry of aircraft as well as its structure parameters. The system is based on multilevel approach to modeling of airframes, which presumes application of four parametrical nested FEM-models built on four basic levels of detailing: airframe, section, panel, element. Each model serves for different tasks of local and global strength and connection between the models is provided automatically, due to the nesting principle. For special non-linear tasks, such as panels' buckling a set of specifies analytical methods are also implemented into the solution procedure.
The main advantages of application of the system for preliminary aircraft design are:
- high accuracy of stress/strain parameters and weight predictions;
- reduced labor input and duration of design procedure;
- possibility to carry out parametric investigations of airframe weight dependence on different structure parameters.

Several examples of application of the system for the preliminary design of aircraft with various configurations are described and estimation of effectiveness of the system is given.

INTEGRATED SIMULATION OF THE PRODUCTION WELL STOCK

Kondratenko F.I.[1,2], Yurkin A.A.[3]
1 - Peter the Great St.Petersburg Polytechnic University, Saint Petersburg, Russia
2 - PJSC Gazpromneft-NNGGF, Noyabrsk, Russia
3 - PJSC Slavneft-Megionneftegaz, Megion, Russia
dostoyewski@yandex.ru

To date, the oil and gas industry does not have a single unified tool for planning and forecasting the well stock work program. Special requirements for the tool are flexibility, efficiency and high-quality technical and economic assessment, taking into account the infrastructure and current macroeconomic parameters for a rapidly changing production program. Accordingly, the critical importance of creating a product that allows for automated control and analysis of key performance indicators of the existing well stock and the preparation of a production program with maximum profitability is now becoming apparent. The introduction of such a development will improve the quality of the production forecast for wells, reduce inefficient investments and the risks of non-fulfillment of the business plan for production in oil and gas companies. This paper discusses the process of developing a software product that allows you to get the above effect.
The development structure currently consists of four modules: a data preprocessing module, a machine learning module, a hydrodynamic models module, and an economics module. The latter will not be considered in this work, since standard calculation algorithms are used, similar to the "Merak" software.
The data preprocessing module is intended primarily for obtaining and preparing data from the corporate databases of company X. The key task of the module is to upload standard forms with merging into one file, as well as data verification.
The machine learning module is designed to build a forecast for liquid production, oil production and water cut for a period of one to 12 months in advance. Inside the module, two logical blocks are implemented: a high-precision predictive model for building a forecast for a month ahead, and a set of models for building long-term forecasts.
The hydrodynamic modeling module is used to obtain additional dependencies ("features") and then use them in the machine learning module. The hydrodynamic model is built, based on pressure conductivity factor, as well as the material balance equation for well cluster.
In the course of this study, developed software makes it possible to predict the parameters of the fund's operation with high accuracy, as well as to evaluate the economic effect. Currently, the issue of introducing a unified predictive system and developing a unified regulatory documentation for software approbation and testing is still open.

References:
1. Maintenance of oil field development using CRM models: monograph / S.V. Stepanov, A.D. Beckman, A.A. Ruchkin, T.A. Pospelov. - Tyumen: CPI "Express", 2021. - 300 s
2. Reimers N.F. Nature management. - M.: Thought, 1990. - 637 p.
3. T. Chen, H. Li, Q. Yang, and Y. Yu. General functional matrix factorization using gradient boosting. (ICML'13), section 1, p. 436–444, 2013.
4. J. Friedman. Stochastic gradient boosting. Computational Statistics & Data Analysis, 38(4):367–378, 2002.
5. T. Zhang and R. Johnson. Learning nonlinear functions using regularized greedy forest. IEEE Transactions on Pattern Analysis and Machine Intelligence, 36(5), 2014.
6. G. Ridgeway. Generalized Boosted Models: A guide to the gbm package
7. X. Meng, J. Bradley, B. Yavuz, E. Sparks, S. Venkataraman, D. Liu, J. Freeman, D. Tsai, M. Amde, S. Owen, D. Xin, R. Xin, M. J. Franklin, R. Zadeh, M. Zaharia, and A. Talwalkar. MLlib: Machine learning in apache spark. Journal of Machine Learning Research, 17(34):1–7, 2016.

EFFECT OF STRAIN RATE ONTO COMPRESSIVE PROPERTIES OF UNIDIRECTIONAL CARBON FIBER REINFORCED PLASTICS

Konev S.D.[1], Konstantinov A.Yu.[2], Basalin A.V.[2], Kuanyshova A.A.[1], Sergeichev I.V.[1]
1 - Skolkovo Institute of Science and Technologies, Center for Materials Technologies, Moscow, Russia
2 - Research Institute of Mechanics, Lobachevsky Nizhniy Novgorod State University, Nizhniy Novgorod, Russia
s.konev@skoltech.ru

Strain-rate dependence of mechanical properties of fiber-reinforced composites is required for many applications involving exposure to impact loads. In order to analyze the dynamic compressive behavior of unidirectional carbon FRP, a validation of shapes and sizes of the specimens and fixtures is required for appropriate calculations and synchronization of stress and strain time plots.
In the present study, we propose a modification of classic split Hopkinson pressure bar setup to achieve the valid compressive failure modes in the specimen's gauge length sections under longitudinal and off-axis loading for strain rate up to 1600 1/s. C-fiber specimens were fabricated by filament winding. Shapes and sizes for the designed specimens were validated by finite element analysis of distributions of stress, strain, and damage parameters within the specimens gauge length during the pulse propagation within SHPB system. As a result, the stress and strain directly calculated in the specimens were compared to ones expressed through the SHPB relationships. High-speed imaging also confirmed the valid failure modes achieved for the given orientation of the specimens. Whereas the standard static tests demonstrated mean values 622 and 116 MPa of compressive strength for specimens loaded along and across fibers correspondingly, more than 20% and 50% increase was observed for those two orientations under high strain rate.
The research was supported by RSF grant number 21-19-00563 (https://rscf.ru/en/project/21-19-00563).

TIME OPTIMIZATION OF CONSTRAINED CONTROL FOR A THERMOELECTRIC SOLID SYSTEM WITH A PELTIER ELEMENT

Gavrikov A., Kostin G.
Ishlinsky Institute for Problems in Mechanics RAS
gavrikov@ipmnet.ru

A solid system consisting of two heat conducting cylinders with a thermoelectric converter (Peltier element) between them is considered. A nonlinear model, which was previously verified by authors, is used to design a constrained control law that allows us to achieve a steady-state distribution of the temperature in one of the cylinders in much less time than the characteristic time of transient processes. The initial-boundary value problem is exactly linearized over temperature by means of feedback linearization. Although the resulting system is nonlinear with respect to a control function, it is possible to construct a finite-dimensional approximation based on analytical solution of the corresponding eigenproblem for a constant control signal. The time-optimal control problem is studied numerically by using this eigenfunction decomposition. To construct admissible control laws, an auxiliary unconstrained optimization problem is introduced. Its cost functional represents a weighted sum of temperature deviation from the desired zero distribution and a penalty for violating an electric power constraint. The control time interval is split into several parts, and on each subinterval the control signal is taken constant. The optimal piecewise constant feedforward control is found partially numerically by applying the gradient descent method. We analyze the proposed control law with respect to the shortest admissible time of the process.

OPTIMAL CONTROL OF LONGITUDINAL MOTIONS FOR AN ELASTIC ROD WITH DISTRIBUTED FORCES

Kostin G.V.[1], Gavrikov A.A.[1,2]
1 - Ishlinsky Institute for Problems in Mechanics RAS, Moscow, Russia
2 - The Pennsylvania State University State College, PA, USA
kostin@ipmnet.ru

The study is devoted to mathematical modeling and optimal control design of longitudinal motions of a rectilinear elastic rod. The control inputs are a force, which is normal to the cross section and distributed piecewise constantly along the rod's axis, as well as two external lumped loads at the ends. It is assumed that the intervals of constancy in the normal force have equal length. Given initial and terminal states with a fixed time horizon, the optimal control problem is to minimize the mean mechanical energy stored in the rod.
To solve the problem, two unknown functions are introduced: the dynamical potential and the longitudinal displacements. As a result, the initial-boundary value problem is reformulated in a weak form, in which constitutive relations are given as an integral quadratic equation. The unknown functions are both continuous in the new statement. For the uniform rod, they are found as linear combinations of traveling waves. In this case, all conditions on continuity as well as boundary, initial, and terminal constraints form a linear algebraic system with respect to the traveling waves and control functions. The minimal controllability time is found from the solvability condition for this algebraic system.

After resolving the system, remaining free variables are used to optimize the cost functional. Thus, the original control problem is reduced to a one-dimensional variational problem. The Euler–Lagrange necessary condition yields a linear system of ordinary differential equations with constant coefficients supplemented by essential and natural boundary conditions. Therefore, the exact optimal control law and the corresponding dynamic and kinematic fields are found explicitly. Finally, the energy properties of the optimal solution are analyzed.

CHANGES IN THE PERMEABILITY OF POROUS SANDSTONES UNDER CYCLIC EXPOSURE

Kozhevnikov E.V.[1], Turbakov M.S.[1], Riabokon E.P.[1], Poplygin V.V.[1], Guzev M.A.[1], Kunitskikh A.A.[1], Qi C.[2]
1 - Perm National Research Polytechnic University
1 - Beijing University of Civil Engineering and Architecture
kozhevnikov_evg@mail.ru

The paper presents the methodology and results of cyclic coreflooding tests. As a porous medium, core samples of consolidated slightly clayey sandstone from one of the oil fields in Russia were used. The presence of permeability hysteresis, which is caused by the migration of natural colloids, was established. Changing the injection rate during flooding contributes to the constant mobilization and migration of colloids. The coreflooding conditions exclude the influence on the permeability of other factors, such as creep and chemical mobilization of colloids. An attempt was also made to evaluate the effect of effective pressure on the permeability of porous sandstone. It has been established that an increase in effective pressure leads to a more intense decrease in permeability, which most likely indicates an additional mobilization of colloids due to the microfractures and compaction of the porous medium. The results of coreflooding showed that porous media with lower permeability are more sensitive to colloid migration and pore pressure changes.
The reported study was supported by the Government of Perm Krai, research project No. C-26/628 dated 05.04.2021.

VOID EVOLUTION KINETICS DRIVEN BY RESIDUAL STRESS IN ICOSAHEDRAL PARTICLES

Khramov A.S.[1], Krasnitckii S.A.[2], Gutkin M.Yu.[1,3,4]
1 - ITMO University, St. Petersburg, Russia
2 - St. Petersburg State University, St. Petersburg, Russia
3 - Peter the Great St. Petersburg Polytechnic University, St. Petersburg, Russia
4 - Institute for Problems in Mechanical Engineering, Russian Academy of Sciences, St. Petersburg, Russia
krasnitsky@inbox.ru

Hollow nanostructures have been attracting a great attention due to their enhanced functional performance in comparison to solid counterparts. In particular, hollow particles are widely employed in different spheres relating to fabrication of modern devices (catalysis, gas sensors, voltaics, plasmonics, etc.). The experimental approaches to hollow particle synthesis are properly investigated and well referred in literature [1,2], while the theoretical aspects of void evolution are still of great concern being limited by the following issues: void stability in single-crystalline and polycrystalline hollow particles of pure elements [3-6], void growth due to the nanoscale Kirkendall effect in bi-metallic particles [3,7], and void formation in terms of residual stress relaxation in multiply twinned particles [8,9]. The latter phenomenon was effectively investigated by a quasi-equilibrium energetic approach in pentagonal whiskers (PWs), icosahedral (IcPs) and decahedral particles (DhPs) without considering the kinetic issue of vacancy diffusion responsible for void formation.

In this report, a kinetic model of vacancy diffusion induced by both the Gibbs-Thompson curvature effect and stress state of the Marks-Ioffe stereo-disclination in a hollow spherical particle is suggested to investigate the void evolution in IcPs. The obtained vacancy concentration profile is employed to derive an equation for the evolution of a central spherical void in an IcP. It is shown that the scenario of void evolution in IcPs strongly depends on the inner-to-outer radii ratio ε_0 at the initial moment of time and on the value of dimensionless parameter α reflecting a contribution of the pressure-induced (drift) vacancy flux between the external and internal surfaces. There is a critical parameter α_{cr} such that for $\alpha > \alpha_{cr}$, the void has a tendency to shrinkage with subsequent collapse for any initial normalized radius ε_0. When $\alpha < \alpha_{cr}$, the following processes can occur: (i) the void shrinking with subsequent collapse, if the initial void radius is less than a critical value, $\varepsilon_0 < \varepsilon_{cr}$; (ii) the void shrinking until it reaches its optimal size, if the initial void radius is larger than its equilibrium value, $\varepsilon_0 > \varepsilon_{eq}$; (iii) the void growing until it reaches its optimal size, if the initial void radius is in the interval $\varepsilon_{cr} < \varepsilon_0 < \varepsilon_{eq}$.
This work was supported by the Russian Science Foundation (grant No. 22-11-00087).

REFERENCES

1. X. Wang et al., Chem. Rev. 116 (2016) 10983.
2. S.F. Soares et al., Proc. Roy. Soc. A 475 (2019) 20180677.
3. A.M. Gusak et al., Philos. Mag. 85 (2005) 4445.
4. A.V. Evteev et al., Philos. Mag. 87 (2007) 3787.
5. F.D. Fischer et al., J. Nanopart. Res. 10 (2008) 255.
6. L. Klinger et al., Scr. Mater. 180 (2020) 93.
7. J. Svoboda et al., Acta Mater. 57 (2009) 1912.

8. A.E. Romanov et al., J. Cryst. Growth 129 (1993) 691.
9. S.A. Krasnitckii et al., Lett. Maters. 12 (2022) 137.

ANALYSIS OF LOCAL FLEXIBILITY OF UNREINFORCED FABRICATED TEES

Ilyin A.A.[1], Krasnitckii S.A.[1,2,3,4]
1 - Peter the Great St. Petersburg Polytechnic University, St. Petersburg, Russia
2 - Institute for Problems in Mechanical Engineering, Russian Academy of Sciences, St. Petersburg, Russia
3 - ITMO University, St. Petersburg, Russia
4 - St. Petersburg State University, St. Petersburg, Russia
ilaxalex@gmail.com

The piping-flexibility analysis is essential to consider a local flexibility of bends [1] and tees [2-4] in the frame of the beam modeling of piping systems. However, the comparable analysis of numerically and analytically is not properly discussed in the aforementioned studies, the flexibility factors obtained by numerical simulation in Ref. [2-4] are not verified by analytical solutions of the shell theory.

This report aims at providing flexibility analysis of the fabricated tees consisting of run-pipe and a branch subjected to external loading (radial force, in-plane and out-plane moments) guided by analytical solutions. The finite element method is employed to determine a local flexibility of tees, it is calculated as a difference between nodal displacement of the shell and the beam models. It is shown that in case of force loading the flexibility factor of the tees with relatively small branch-to-run diameter ratio ($d / D < 0.5$) takes almost a constant values if the run and branch length is limited by $L < 20 D$. The result is verified by an analytical solution for the cylindrical shell subjected to a concentrated radial force [5]. As for tees with $d / D > 0.5$, the flexibility factor has strongly nonmonotonic dependence on the pipe length L. This fact makes it difficult to determine a correct flexibility factor corresponding to the local compliance of shell intersections. Besides, it is demonstrated that in case of moment loading, the flexibility factors are in a good agreement with analytical and experimental results presented in Ref. [2-4].

REFERENCES

1. A.R.C. Markl, Trans. ASME, 77 (1955) 143.
2. L. Xue, J. of Pres. Ves. Tech., 128 (2006) 89.
3. A. Pauliin, ASME Std. Tech. (2014) 375.
4. T Fujimoto et al., J. of Pres. Ves. Tech., 110 (1988) 374.
5. V. M. Darevskii, Prochn. & Dinam. Avia. Dvig. (1964) 23 (in Russian).

DYNAMICS OF MATTER AND ENERGY

Krivtsov A.M.[1,2]
1 - Peter the Great St.Petersburg Polytechnic University, Russia
2 - IPME RAS, Russia
akrivtsov@bk.ru

According to Pavel A. Zhilin, mechanics is a universal tool for describing almost any phenomena in the physical world. In the current lecture, this concept is applied to the problems of mass and energy transfer, especially for the case when they exhibit dynamic and/or wave behavior.

Wave energy transfer in discrete and continuum systems is analyzed, and an inhomogeneous chain of interacting particles is considered as a basic example. The evolution of an arbitrary perturbation of finite energy is studied. The analogy between mass transfer and energy transfer is used to develop mathematical tools that allow applying the equations of classical dynamics of matter to describe the dynamics of energy. The concepts of a carrier and a phantom are introduced, where a carrier is a medium capable of transmitting energy, a phantom is a virtual material body having a mass distribution proportional to the distribution of energy in the carrier. It is shown that for an inhomogeneous chain, the phantoms satisfy Newton's second law of dynamics. For specific systems, the constitutive equations for the net force acting on the phantom are derived, resulting in closed dynamics equations. It is shown that, depending on the ratio of the transport and dispersion parameters, the phantom can behave either as a wave or as a particle.

Applications of energy dynamics to describe processes in other fields of modern physics, such as quantum mechanics, electrodynamics and general relativity, are discussed. The concept is proposed, according to which matter can be considered as a phantom in some carrier, which is a different entity than matter. Based on the presented concept, a qualitative explanation of some open questions of modern physics is proposed.

NONLINEAR DYNAMICS OF MESHED NANOPLATE TAKING INTO ACCOUNT SELF-HEATING

Krylova E.Yu.
Saratov State University, Saratov, Russia
kat.krylova@bk.ru

In this work, a mathematical model of the micropolar mesh plate nonlinear dynamics is constructed taking into account the coupling of deformation and temperature fields. The plate material is elastic, isotropic and homogeneous.
The plate element motion equations, boundary and initial conditions are obtained from the variational principle of Ostrogradsky-Hamilton, taking into account the Kirchhoff hypotheses. Geometric nonlinearity is taken into account according to Theodor von Karman's theory. In order to take into account scale effects, the mathematical model of plate oscillations is built on the basis of the micropolar theory with constrained rotation of particles. In this case, the displacement and rotation fields are not considered independent. The constitutive relations for the micropolar plate are written taking into account the Duhamel-Neumann hypotheses. The mesh structure is taken into account according to the G. I. Pshenichnov's theory, according to which a regular system of densely spaced edges can be replaced by a continuous layer. A related thermodynamics problem is considered.
The resulting system of nonlinear partial differential equations is reduced to a system of ordinary differential equations by the finite difference method with a second-order approximation of accuracy. The Cauchy problem is solved by the Runge-Kutta method. An original software package has been created that makes it possible to study the statics and nonlinear dynamics of a meshed nanoplate depending on its geometry, physical parameters, and external transverse and longitudinal loads.
A numerical experiment is presented.
The work was carried out with the support of the RSF № 22-21-00331

GEOMETRICALLY AND PHYSICALLY NONLINEAR DYNAMICS OF FUNCTIONAL GRADIENT EULER-BERNOULLI NANOBEAMS UNDER NEUTRON IRRADIATION

Krysko A.V., Papkova I.V., Krysko V.A.
Yuri Gagarin State Technical University of Saratov
ikravzova@mail.ru

A mathematical model of functional gradient Euler-Bernoulli beams is constructed taking into account geometric and physical nonlinearities under neutron irradiation conditions. When constructing the mathematical model, the following hypotheses and assumptions were used: the beam material is a composite consisting of isotropic homogeneous elastic ceramics and aluminum, which is inhomogeneous at the point, depends on the stress–strain state and neutron irradiation. Nanoeffects are taken into account according to the modified moment theory of elasticity. Geometric nonlinearity – according to the von Karman model, the Euler-Bernoulli hypothesis is accepted. The required partial differential equations, boundary and initial conditions are derived from Hamilton's principle. An effective solution method has been developed, consisting of iterative procedures nested into one another, the second-order accuracy finite differences method in spatial coordinates and methods such as Runge-Kutta and Newmark in time and Birger's method of variable elasticity parameters. The results reliability is ensured by the convergence of the above iterative procedures. Static tasks are obtained using the steady solution method, which is a continuation method by parameter. Using the developed software package, physically and geometrically nonlinear Euler-Bernoulli nanobeams are investigated depending on the boundary conditions, relative thickness, nanoparameter, dependence diagrams of the stress intensity on strain intensity, and the direction of neutron irradiation.
The work was carried out with the support of the RSF grant № 20-08-00354 A.

MATHEMATICAL MODEL OF NON-LINEAR VIBRATIONS OF A THERMOSENSITIVE CLOSED CYLINDRICAL SHELL

Yakovleva T.V.[1], Krysko-jr. V.A.[2]
1 - Lavrentyev Institute of Hydrodynamics of Siberian Branch of Russian Academy of Sciences
2 - Lodz University of Technology
yan-tan1987@mail.ru

Questions of the existence of a solution in problems of mechanics and physics are related to the methods of qualitative study of operator equations and are of great interest. They provide a rational way to test the adequacy of a theory that brings together the facts and phenomena of the physical world into a certain mathematical scheme, not related to the conduct of experiments. In this case, two possibilities are used to solve this problem. On the one side, this is the theory of multidimensional singular potentials and singular integral equations, on the other side, the theory of generalized solutions of differential equations (methods of Hilbert spaces, variational methods).
In this paper, we use the second approach, which is more general and covers the case of variable coefficients and boundary conditions. The main steps in applying this approach are: derivation of a priori estimates; use of these

estimates. In this case, the choice of function spaces in which the solution is sought plays an essential role. The compactness method is used to obtain and use a priori estimates.
The results obtained in this work are a generalization of known results for the case of the problem of oscillations of a thermosensitive closed cylindrical shell. The main attention is paid to the formulation and proof of the existence theorem for this problem in the case of a sufficiently regular domain under Dirichlet boundary conditions. The approach implemented in the work is based on the application of the Green's function.
This work has been supported by the Russian Science Foundation under the Grant № 22-11-00160.

MATHEMATICAL MODEL OF EXTRUSION IN FDM 3D PRINTING TECHNOLOGY

Kudryashova O.B., Toropkov N.E., Lerner M.I., Vorozhtsov A.B.
National Research Tomsk State University, Tomsk, Russia
olgakudr@inbox.ru

We proposed a mathematical model of flow and extrusion in the 3D printing process (FDM technology). We considered compositions based on a polymeric binder and bimodal powders.
The model is based on fluid mechanics and uses conservation laws taking into account friction losses and local resistance losses. Under given assumptions, we have obtained an expression for the rate of outflow of the mixture from the nozzle, depending on its geometry, inlet pressure, and viscosity of the material.
It is known that the viscosity of the initial mixture depends on the temperature, pressure, concentration, and dispersion of particles. A parametric study of the model was carried out.
Commonly used additive technologies for working with metal powders are SLS (Selective Laser Sintering) and SLM (Selective Laser Melting). They involve the use of expensive and complex equipment, including a powerful laser. FDM 3D printing technology (fused deposition modeling) is based on the use of a relatively simple and inexpensive printer. We have considered not the usual polymer thread for this printer, but compositions with metal powders. The problem with using FDM technology lies in the high viscosity of the material, which is especially high at high particle concentrations.
We have obtained experimental data on the rheology of compositions based on bimodal powders containing micro- and nanoparticles. These data are used as the basis for calculating the extrusion rate of compositions in FDM 3D printing of the considered compositions.
It has been shown that compositions using bimodal powders have unusual rheological properties in comparison with polymer compositions with a relatively low content of particles and in comparison with a composition based on single-modal micron-sized particles. The results of calculations of the extrusion rate depending on temperature, pressure, and dispersion of powders are given in the report.

The study was supported by a grant from the Russian Science Foundation (project No. 21-79-30006).

ON THE INFLUENCE OF RELAXATION PROCESSES ON THERMOACOUSTICS OF MATERIALS

Morozov N.F.[1,2], Indeitsev D.A.[1,2,3], Muratikov K.L.[4], Semenov B.N.[1], Vavilov D.S.[2,5], Kudryavtsev A.A.[3]
1 - St. Petersburg State University, St. Petersburg , Russia
2 - Institute for Problems in Mechanical Engineering, St. Petersburg, Russia
3 - St. Petersburg Polytechnic University, St. Petersburg, Russia
4 - Ioffe Institute, St. Petersburg, Russia
5 - A.F. Mozhaysky Military-Space Academy, St. Petersburg, Russia
londr@yandex.ru

As is known the relaxation process characterizes the tendency of any physical system to equilibrium. This process doesn't proceed with the same rate for each of internal degrees of freedom describing the dynamics of a physical system. It is a multistep process with many relaxation times, characterizing it at different scale levels. For problems of classical continuum mechanics, by virtue of considering only the collective motion of particles in an elementary volume, the relaxation processes satisfy the well-known Euler equations and differ only due to different constitutive equations.The situation changes when the description of a material requires taking into account the influence of new degrees of freedom on the collective motion of particles, for example, their relative motion or the appearance of defects. In this case, the model of interpenetrating continua or the free energy functional with the parameter of impurity concentration are usually used allowing one to obtain new equations with effective parameters varying according to the kinetic and diffusion equations. In this case the general relaxation process has two spectral responses under dynamic loading. The first one is connected with the propagation of waves in the occupied region of a continuous medium, whereas the second one is generated by the motion of additional degrees of freedom. This process is usually superimposed on the collective dynamics and thus, the problem of extracting the information about the microstructure from the general signal arises.In the present article it is shown that the presence of defects in material for a certain duration of heat exposure leads to the necessity of taking into account the dependence of the linear thermal expansion coefficient on their mobility, which determines its operator form. We consider a one dimensional thermoelastic problem with the localized mass on the surface acting as the defect. In this case the transfer function defining the dynamic component of the effective linear thermal expansion coefficient can be obtained. The reduction of the deformation wave amplitude due to the presence of the inclusion is demonstrated.

INVESTIGATION OF NON-REGULAR GRID STRUCTURAL LAYOUTS FOR LATTICE FUSELAGE BARRELS

Levchenkov M.D., Dubovikov E.A., Shanygin A.N., Mareskin I.V., Mirgorodskiy Y.S., Belikov S.A.
Central Aerohydrodynamic Institute (TsAGI)
mihalevch@mail.ru

The emergence of composite materials (CM) in aircraft construction has opened up new possibilities for increasing the weight efficiency of aircraft structures and has set the designers the task of finding optimal structural layout (SL) for them. The time has shown that the use of composite materials in frames of traditional (skin) structural layout is associated with the appearance of problems connected with low impact strength and the presence of stress concentrators at the microlevel due to structural heterogeneity, which is unusual for metals, but typical for composites.
To overcome these problems, it is rational to use a lattice structural layout, which advantageously uses pros of composite materials and levels out the cons. This type of SL came to aviation from space industry, where it has been successfully used in launch vehicles for a long time, and by now there is a number of studies on the use of lattice structural layouts in real aircraft projects.
One of the tasks in creating a lattice SL is to design the optimal geometry of the grid structure. By changing the shape of the lattice along the surface of the fuselage, it becomes possible to achieve the lowest weight while meeting the necessary strength requirements. This study presents the investigation of the optimal shape of the irregular lattice structure for grid fuselage barrels.

UNSTEADY TWO-TEMPERATURE HEAT TRANSPORT IN MASS-IN-MASS CHAINS

Liazhkov S.D.[1,2], Kuzkin V.A.[1,2]
1 - Peter the Great St.Petersburg Polytechnic University
2 - Institute for Problems in Mechanical Engineering of the Russian Academy of Sciences
sergeiliazhkov@gmail.com

We investigate the unsteady heat transport in an infinite mass-in-mass chain with a given initial temperature profile. The chain consists of two sublattices: the beta-Fermi-Pasta-Ulam-Tsingou (FPUT) chain and oscillators (of a different mass) connected to each FPUT particle. Initial conditions are such that initial kinetic temperatures of the FPUT particles and the oscillators are equal. Using the harmonic theory, we analytically describe evolution of these two temperatures in the ballistic regime. In particular, we derive a closed-form fundamental solution and solution for a sinusoidal initial temperature profile in the case when the oscillators are significantly lighter than the FPUT particles. The harmonic theory predicts that during the heat transfer the temperatures of sublattices are significantly different, while initially and finally they are equal. This may look like an artifact of the harmonic approximation, but we show that it is not the case. Two distinct temperatures are also observed in the anharmonic case, even when the heat transport regime is no longer quasi-ballistic. We show that the value of the nonlinearity coefficient required to equalize the temperatures strongly depends on the particle mass ratio. If the oscillators are much lighter than the FPUT particles, a fairly strong nonlinearity is required for the equalization.

THREE-DIMENSIONAL (3D) PRINTING TECHNOLOGY FOR MEDICINE

Suvorov V.V.[1,2], Loboda O.S.[1], Kulczycki I.A.[1], Balakina M.E.[1], Loboda M.N.[1], Rusalovskaya E.A.[1]
1 - Peter the Great St. Petersburg Polytechnic University, St. Petersburg, Russia
2 - Saint Petersburg State Pediatric Medical University, St. Petersburg, Russia
loboda_o@mail.ru

Today, the development of methods for surgical correction of various diseases is largely associated with technological progress. Three-dimensional printing technology might be a key in transforming clinical practice and significantly improve the results of the treatment. The introduction of this technique in pediatric cardiac surgery will allow to study the features of the anatomy and spatial relations of the defect before surgery, anticipate possible difficulties and determine the optimal tactics for surgical correction. The goal of our study was creation of an assistance system for cardiac surgeons in planning operations using artificial intelligence and 3D printing methods.
An algorithm has been developed that allows, based on CT images, to create a 3D model of the heart and great vessels suitable for 3D printing. Several models of the heart and great vessels have been printed and tested. Studies have been carried out on the selection of printing modes and materials so that the models are as similar as possible in physical and mechanical properties to living organs.

References
[1] Suvorov V.V., Zaitsev V.V., Kupatadze D.D., Krivoshchekov E.V., Loboda O.S., Lezhnev A.A. APPLICATION OF THREE-DIMENSIONAL PRINTING TECHNOLOGY IN PLANNING SURGICAL TREATMENT OF COMPLEX CONGENITAL HEART DISEASES. Cardiology and cardiovascular surgery. 2020. V. 13. No. 4. S. 294-298.
[2] Austin H. Williams, Sangchul Roh, Alan R. Jacob, Simeon D. Stoyanov, Lilian Hsiao & Orlin D. Velev. Printable homocomposite hydrogels with synergistically reinforced molecular-colloidal networks. NATURE COMMUNICATIONS | (2021) 12:2834 | https://doi.org/10.1038/s41467-021-23098-9.

TESTING OF PROGRAMS USED IN DISCRETE ELEMENTS METHOD SIMULATION

Lobovikov D.V., Kharchenko A.V., Matygullina E.V.
Perm National Research Polytechnic University, Russia
ppk2004@inbox.ru

Discrete element method (DEM) simulation is used to study the dynamics of granular materials. To verify the software implementation of the method, as well as to choose the integration time step, reliable test problems are required. Analytical solution for the test is obtained using impact theory. Variants of collision of two spherical particles with friction sliding and rotation are considered. For the analytical solution, the loss of normal velocity upon impact is described by the recovery coefficient, and gravity is not taken into account. Solutions are obtained for the case of identical particles, as well as for particles of different diameters. The analytical solution is used to verify the own program of the DEM method. A series of computational experiments was carried out with the choice of different parameters of the colliding particles and the parameters of the method. Compares tangential, normal particle velocities and particle rotation velocities after collision for analytical solution and simulation. It is shown that after the impact these parameters have a qualitative and quantitative similarity. As a parameter characterizing the accuracy of calculations, the modulus of the speed of movement of the part after the impact was chosen.
The next series of tests is obtained for statics. An analytical solution is obtained for three spherical particles in a static position. The scheme of the three particles is as follows. Three spherical particles have the same size and properties, two spherical particles are located next to each other on a horizontal surface, the distance between them is less than the diameter of the particle, the third particle is located on top symmetrically on the first two, touching them both. The problem is to determine the conditions under which the three particles remain static. The next test differs from the previous test in that the upper particle has a mass greater than the mass of particles located on a horizontal surface. The obtained analytical conditions for static immobility remained the same. The next test differs from the previous test in that two particles placed on a horizontal surface have different diameters. The next test differs from the previous tests in that four particles are used. Three particles are located on a horizontal surface, the distances between them are equal. A fourth particle is installed on top of them in the center. The next test differs from the previous test in that three particles placed on a horizontal surface have different diameters. Analytical solutions are obtained for all tests. When modeling, the coefficient of friction is set, then, such a maximum distance between particles is searched for, at which the particles are statically stable. The resulting simulation result is compared with the analytical solution.

NONLINEAR MODAL INTERACTION BETWEEN LONGITUDINAL AND BENDING VIBRATIONS OF A MICROBEAM RESONATOR UNDER PERIODIC OPTO-THERMAL EXCITATION

Lukin A.V.[1], Indeitsev D.A.[2], Popov I.A.[1]
1 - Peter the Great St.Petersburg Polytechnic University
2 - Institute for Problems in Mechanical Engineering of the Russian Academy of Sciences (IPME RAS)
lukinalexei@yandex.ru

The work is devoted to investigation of the nonlinear dynamics of coupled longitudinal-flexural vibrations of a microbeam clamped at both ends - the basic sensitive element of a promising class of microsensors of various physical quantities - under laser opto-thermal action in the form of periodically generated pulses acting on a certain part of the surface of the beam element. Two geometric configurations of the resonator are considered, which correspond to two fundamentally different scenarios for the generation of mechanical oscillations using laser action. The first case corresponds to the classical scenario of excitation of the primary parametric resonance for the lower bending mode of microbeam vibrations. In this case, the laser impact is assumed to be uniformly distributed over the entire surface of the microbeam, which ensures the absence of longitudinal oscillations of the resonator and the excitation of parametric bending oscillations due to the presence of an axial temperature force that varies harmonically with time. The second case is characterized by laser generation of coupled longitudinal-flexural oscillations of the resonator under conditions of external primary parametric resonance for the working bending mode of oscillations and internal submultiple resonance between the considered bending and longitudinal modes. The possibility of generation in the system of the longitudinal-bending mode was found, the frequency of the slow envelope of which essentially depends on the parameter of the internal frequency detuning, which is directly related to the magnitude of external disturbances subject to high-precision measurement.

NEW METHOD FOR REDUCING ANY MINDLIN-TYPE SECONDARY GRADIENT ELASTICITY TO TWO-PARAMETER THEORIES WITHOUT LOSS OF GENERALITY

Lurie S.A., Belov P.A.
Institute of Applied Mechanics of RAS, Moscow, Russia
salurie@mail.ru

Mindlin's type gradient theories of elasticity are considered, which are the basis for the theoretical description of materials, taking into account scale effects. For the first time, a procedure is proposed that allows one to significantly simplify applied gradient elasticity theories. It has been established that for the canonical representation of the potential energy of Mindlin's gradient theories of a general form, it is always possible to introduce a quadratic form, which is a convolution of vectors. It is proved that for the remaining components of the potential energy density, it is always possible to distinguish divergent terms, which should be equal to zero for gradient models that are consistent everywhere. As a result, we found that any gradient general five-parameter Mindlin-type theory is reduced to a two-parameter theory for which the potential energy density is determined by the potential and vortex displacement fields and does not contain bilinear forms. A class of new models of gradient elasticity, called "vector models", is formulated, in which almost the classical form of static boundary conditions is provided. This makes it possible to avoid the difficulties typical of gradient theories associated with the implementation of boundary conditions on surface edges in theoretical and numerical simulations. It is proved that the implementation of solutions to the boundary value problems of vector models requires the obligatory fulfillment of the symmetry conditions for the tensor of gradient elastic moduli with respect to the last indices in each triple of indexes -conditions with respect to the order of differentiation. The procedure for complying with these conditions is indicated. Two variants for the two parametric theories with different forms of the boundary conditions are derived using the variational approach. First variant is derived taking into account the vector gradient theory without the boundary conditions on the edge. It has simplified traction boundary conditions formulated only with respect to the total stress tensor. Second variant is derived following general procedure exploiting surface divergence theorem, which results in a more complex form of the boundary conditions on the body surfaces and edges. Correctness of the two presented formulations of the theory is discussed. Examples of analytical solutions for the problems of pure bending, pressurized sphere and radial vibrations of sphere are obtained and compared for the both variants of the theory.
The authors would like to acknowledge the financial support of the Russian Science Foundation under the grant 20-41-04404 issued to the Institute of Applied Mechanics of Russian Academy of Sciences.

ON THE RECURRENCE TIME OF KINETIC TEMPERATURE IN A ONE-DIMENSIONAL HARMONIC CRYSTAL

Lykov A.A.
Lomonosov Moscow State University, Russia
alekslyk@yandex.ru

In the paper [1] kinetic temperature in a one-dimensional harmonic crystal was studied. The effect of thermal echo was discovered and investigated. This effect one can observe on the time scale of order N, where N is the number of particles and large enough. Our system is conservative and Poincare recurrence theorem holds. Recurrence theorem and damping behavior of kinetic temperature are contradictory. The reason is that recurrence time is much larger than N. So, the recurrence appears on the time scale of higher order. It is turned out that the recurrence time grows exponentially with N and relates to the invariant measure of some small set in the phase space. In the talk we will discuss how to estimate the mean recurrence time of the kinetic temperature, its relation to the large deviation theory. Theorem about upper and lower bounds will be formulated.
[1] Murachev A., Krivtsov A, Tsvetkov D., “Thermal echo in a finite one-dimensional harmonic crystal”, Journal of Physics: Condensed Matter, 31, 9, 2019.

UNIAXIAL HIGH STRAIN RATE TENSION METHOD USING PULSED MAGNETIC PRESSURE

Alekseev D.I., Zhukov D.V., Krivosheev S.I., Magazinov S.G., Ostropiko E.S.
Peter the Great St.Petersburg Polytechnic University (SPbPU)
magazinov_sg@mail.ru

It is known that the dynamic mechanical properties of materials differ from the static ones, in particular, metals are strengthened with an increase in the strain rate. To test the dynamic properties of materials, there are various methods such as Taylor, Hopkinson-Kolsky, Hauser, spall, etc. These methods require an impulse action, which can be generated by such methods as detonation of an explosive, high-pressure gas, collision with a rapidly moving body, etc. A pulsed magnetic field can also be used to form a impact action, which is considered in this paper.
A magneto-mechanical system for loading samples for testing their mechanical properties at a strain rate of $\sim 10^3$ - 10^4 1/s has been developed. This system consists of a pulsed current generator (PCG), flat copper conductors, two non-

deformable steel plates and a sample. The PCG generates a pulsed current flowing through flat closely spaced confuctors, between which a pulsed magnetic field and pressure are formed. Flat conductors transmit mechanical action on steel non-deformable plates to which a metal sample is attached, resulting in uniaxial direct tension of the sample.
The simulation of the pulsed magnetic field of the system of flat conductors is performed and the magnetic pressure is calculated by the finite element method in the Comsol software. Simulation of dynamic deformation of samples was performed using the Johnson-Cook high strain rate deformation model in the Ansys Autodyn software. Optimal geometric parameters have been selected to ensure the sensitivity of the magneto-mechanical system to changes in sample properties by 10% or more.

NON-SINUSOIDAL WAVES IN A METAMATERIAL, SPECIFIED AS A NONLINEAR ELASTIC LATTICE WITH A CENTER OF SYMMETRY

Malkhanov A.O., Erofeev V.I.
Mechanical Engineering Research Institute of the Russian Academy of Sciences – Branch of Federal Research Center "Institute of Applied Physics of the RAS", Nizhny Novgorod, Russia
alexey.malkhanov@gmail.com

At present time, technologies for creating promising structural materials with micro- and nanostructure are being intensively developed. These materials include metamaterials - a new class of substances with a complexly organized internal structure, which has unique physical and mechanical properties [1]. They first appeared in the field of optics and photonics [1], but now they are increasingly found in other fields as well. For example, acoustic metamaterials [3 - 5] are widely used, in particular, as super absorbers of sound [6].
It is obvious that the creation of metamaterials in the absence of adequate mathematical models is extremely difficult.
Guided by the mathematical analogy between acoustic and electromagnetic waves, many researchers have tried to construct continuous models of mechanical metamaterials. However, it was not possible to achieve great success on this path, since the mechanical analogs of real-life materials with negative dielectric constant are deformable solids with negative mass, density, or negative modulus of elasticity. And such materials do not exist in nature.
It was possible to avoid this drawback on the way of structural modeling of metamaterials, which makes it possible to construct their discrete mathematical models and, if necessary, to carry out their continualization [7].
In this work, we propose a mathematical model of a metamaterial represented as a nonlinear elastic two-mass chain with a center of symmetry. The model was continualized. The conditions for the formation of non-sinusoidal strain waves have been analyzed.
References
1. Yu.V. Gulyaev, A.N. Lagarkov, S.A. Nikitov, Metamaterials: fundamental research and application prospects., Vestnik RAN, Vol. 78, issue 5, p. 438-457, 2008.
2. S. Zhu, X. Zhang, Metamaterials: artificial materials beyond nature, National Science Review. 5 (2018) 131.
3. Special issue on acoustic metamaterials, J. Acoust. Soc. Am. 132 (2012) 2783-2945.
4. P.A. Deymier (ed), Acoustic Metamaterials and Phononic Crystals, Springer-Verlag, Berlin, 2013.
5. R.V. Craster, S. Guenneau (eds), Acoustic Metamaterials: Negative Refraction, Imaging, Lensing and Cloaking, Springer, Dordrecht, 2013.
6. E.L. Aero, Essentially nonlinear micromechanics of a medium with a variable periodic structure., Vol. 1, issue 3., p. 130-176, 2002.
7. A.I. Potapov, Waves of deformation in a medium with an internal structure., Nonlinear waves'2004, Nizhny Novgorod, IAP RAS Publishing House, p. 125-140, 2005.

NONLINEAR DEFORMATION OF A PLANE WITH A RIGID ELLIPTICAL INCLUSION LOADED BY FORCE AND MOMENT

Malkova Yu.V.
St. Petersburg State University
y.malkova@spbu.ru

In this paper, an exact analytical solution of a nonlinear elasticity theory problem for a plane with a rigid elliptical inclusion is obtained. In the center of the inclusion a concentrated force and a moment are applied. At infinity, the nominal stresses are zero. Under the action of an external force and moment, the elliptic inclusion gains translational motion and rotation around the center. The elastic properties of the plane are modeled by the harmonic John material. The nominal stresses and displacements are expressed through two analytical functions of a complex variable. They are determined from the boundary conditions on the inclusion contour. A solution of the second basic nonlinear boundary value problem is presented. The problems of the action of a concentrated force and moment on an elliptic core in a plane are considered separately. The effect of tension by force along coordinate axes on the value of stresses depending on various parameters of the problem is investigated. The nominal radial and circumferential stresses on the elliptic contour are calculated.

PECULIARITIES OF NUMERICAL SIMULATION OF NATURAL CONVECTION IN HORIZONTALLY BASED PLATE-FIN HEAT SINKS

Mankov E., Pavleyno M.
Saint Petersburg State University, Saint Petersburg, Russia
mankov.elisey@bk.ru

Passive plate-fin heat sinks are a fairly common type of cooling systems in modern devices. There is often a necessity of a detailed study of the convective flows in such heat exchangers and the search for their optimal parameters to achieve maximum heat dissipation capacity. One of the widely used methods of designing heat sinks and determining the optimal parameters is finite element simulation in specialized software packages.

When using finite element simulation to study horizontally based plate-fin heat sinks the question of the need to take into account two types of edge effects - *finite number of fins* and *finite fin length* - arises acutely, because adding them into consideration significantly increases the complexity of the model and, as a consequence, the calculation time. Often the authors of scientific papers use the most complete model of a heat sink, taking into account both types of edge effects [1,2], and do not compare the results with the simplified models. In this regard, it was decided to make this comparison and investigate the influence of the aforementioned edge effects on the gas-dynamic processes in horizontally based plate-fin heat sinks and on the one of the key parameters of such systems - the optimum fin spacing s_{opt}.

Three models were considered: 1) heat sink without edge effects (infinite number of infinitely extended fins); 2) heat sink with a finite number of infinitely extended fins; 3) heat sink with a finite number of finite length fins. It was determined that the model without edge effects is not applicable to the design of heat sinks due to the lack of solution convergence by the sizes of the computational domain, while for the other two models such a problem was not observed. To understand in more detail the reasons for this behavior of the solution in model 1, we investigated how the sizes of the computational domain affects the convergence in model 2 as the number of fins increases, and found some interesting features. Also, the calculations showed that under the conditions considered, neglecting the finite fin length does not change the value of s_{opt}, but only changes the heat transfer coefficient.

[1] Dialameh, M. Yaghoubi, O. Abouali "Natural convection from an array of horizontal rectangular thick fins with short length" // J. Applied Thermal Engineering / 2008. 2371–2379 p.
[2] Senol Baskaya, Mecit Sivrioglu, Murat Ozek "Parametric study of natural convection heat transfer from horizontal rectangular fin arrays" // J. Thermal Science / 2000. 797-805 p.

ON FAST ALGORITHMS IN LAGRANGIAN VORTEX METHODS FOR VORTEX PARTICLES INTERACTION SIMULATION

Marchevsky I.K., Ryatina E.P.
Bauman Moscow State Technical University
iliamarchevsky@mail.ru

In the low-speed subsonic problems of flows simulation around bodies, meshless purely Lagrangian vortex particle methods can be very efficient due to rather low computational complexity and memory requirements. Vorticity field is considered as a primary calculated variable and is represented through large number of elementary vorticity carriers – vortex particles. The velocity field can be reconstructed using the Biot – Savart law, that expresses their mutual influences. Thus, the 'direct' calculation of the particles' velocities is extremely time-consuming operation since its computational complexity is squared with respect to number of particles. The only efficient way to complexity reduction is the usage of the approximate fast methods having quasilinear complexity. Although fast methods are well-known and widely used, the specific features of the vortex methods allow developing their more efficient implementations.

The 'hybrid' modification of the fast algorithm is suggested, that combines advantages of two most popular approaches: the Barnes – Hut and Fast Multipole Methods. Its parallel (OpenMP and CUDA) implementations are presented. The proposed method is tree-based. For each leaf-cell the proximity criterion is checked that determines far-placed cells, for which multipole expansion is acceptable instead of direct influence calculation, and rather compact zone of neighbouring cells (that are always leaves too), which influence should be taken into account according to the Biot – Savart law. For efficient GPU implementation it seems suitable to construct a tree structure until each leaf-cell contains a single particle, while for CPU implementation the tree-structure is constructed until target level is achieved, so a leaf-cell may contain several particles and straightforward computation of influences for all particles is replaced with usage of local expansions, constructed at the leaf-cell center.

The tree traversal is performed for the list of leaf cells, so the simplest way to parallelization using OpenMP or MPI+OpenMP is trivial. For OpenMP threads, it is achieved by dynamic scheduling usage with a rather small block size. The resulting speedup corresponds to approx. 80 % efficiency (with respect to 1-thread sequential mode).

The GPU implementation is based on the known freely available `gravitational' N-body code and is adapted by the authors for vortex methods: the possibility of the higher-order multipole models accounting is implemented (without their local expansions, performed on CPUs). Numerical experiments are performed for CPUs and GPUs of different generations. All the parameters of the algorithms are optimized to achieve the lowest computational complexity. For moderate accuracy, GPU-code for the most powerful accelerator Tesla A100 is about 3.5 times faster than CPU code on 32-core processor Intel Xeon Gold 6254. Time of computations for 2 millions of vortex particles on Tesla A100 is about 50 ms. The developed algorithms allow for significant resolution improvement in vortex particle method.

AN OPEN-ACCESS SOFTWARE FOR THE CALCULATION OF EFFECTIVE ELASTIC AND CONDUCTIVE PROPERTIES OF ELASTIC MEDIA. APPLICATION TO A CASE STUDY OF A RESERVOIR ROCK SAMPLE

Markov A.[1], Díaz-Viera M.A.[2], Coronado-Gallardo M.[2]
1 - Tecnologico de Monterrey, Monterrey, Mexico
2 - Instituto Mexicano del Petroleo, Mexico city, Mexico
a.markov@tec.mx

An application of the open-access software destined for fast calculation of the contribution of an individual inhomogeneity of one of two types (cracks and solid inclusions) to the elastic and/or conductive properties of an infinite elastic medium is presented. The software was applied to the calculation of effective elastic properties of an oil reservoir rock sample extracted from a wellcore fragment containing isolated pores. The pore geometries were obtained by a 3D image from an X-ray tomography previously processed and converted into stereolithography (.stl) format. The data required for the calculations besides the shapes of the inhomogeneities is the Young's modulus and the Poisson's ratio of the matrix (in the isotropic case).
The contribution of each pore to the elastic properties of the rock sample was calculated by the efficient numerical mesh-free method based on Gaussian approximating functions [1]. The problem is reduced to a system of 2D integral equations for the crack opening vector or 3D volume integral equations for the stress/strain field and electric or heat field/flux inside the inclusion. Than the 2- or 3D region of interest is covered by a regular node grid. For discretization of the integral equations, Gaussian approximation functions centered at the nodes are used. Once the problem is solved, the contribution tensor to the effective elastic properties is calculated directly from the solution.
Afterwards, the overall effective elastic properties were obtained by the Mori-Tanaka scheme. The results obtained show a good agreement with analytical models; however, the proposed methodology is straightforward and it was possible to detect even slight anisotropy of the effective elastic properties.
As a future work, experimental measurements of the elastic properties of the sample and their comparison to the numerical results are considered.

References:
[1] A. Markov, A. Trofimov, I. Sevostianov (2020) A unified methodology for calculation of compliance and stiffness contribution tensors of inhomogeneities of arbitrary 2D and 3D shapes embedded in isotropic matrix – open access software. International Journal of Engineering Science, 157, 103390

MINE FLOOR STABILITY UNDER THE ACTION OF HEAVY STRIKER

Martemyanov A.N.
EuroChem Project, Saint-Petersburg, Russia
andrey.martemyanov@eurochemproject.ru

To gain an appropriate level of safety during underground works necessary to consider both initial in-situ stress and different affects due to technological procedure. Falling of heavy load is able to cause significant harm for mine and may lead to total destruction of underground structures and machines. Present work is dedicated to analysis of floor sustainability between two levels of mine subjected to punch of cylindrical impactor. Elastic wave propagation has been calculated as a solution of dynamic problem according to given geometry. Based on this, fractured areas have been estimated by several damage criteria appropriate for dynamic conditions. Depending on loading conditions and material properties areas of different destruction types may be distinguished: volumes with set of fractures, fragmented and pulverized. Initial problem has been considered in the cases of homogeneous and reinforced concrete with the presence of additional guiding structures and a lay of fine material as a damper.
Analytical results have been approved by numerical calculations with FEM.

METHOD OF RESCUING A SIX-LEGGED ROBOT FROM AN EMERGENCY POSITION ON AN UNEVEN SURFACE

Golubev Yu.F.[1,2], Koryanov V.V.[2], Melkumova E.V.[1]
1 - Lomonosov Moscow State University, Moscow, Russia
2 - Keldysh Institute of Applied Mathematics, RAS, Moscow, Russia
elena_v_m@mail.ru

A method of rocking of the six-legged robot to ensure its overturn from the "upside down" position is proposed. As a support, we consider an inclined plane with a slight slope towards the flip, with a pit and optionally with a bump next to it. The position of the fixed support can be set by sequential rotations around two different axes. It is shown that the overturn is possible with the help of cyclic movement of the legs, if the body has an upper shell in the form of a truncated cylinder. The legs on the pre-chosen edge of the body through which the flip should occur, are passive, and straightened along the body so that they do not interfere with the flip. The legs on the opposite edge are active; they perform synchronous movement in a plane perpendicular to the longitudinal axis of the body, with a fixed angle in the knee. The results of simulation of the full dynamics of the robot in contact with the support by means of the "Universal mechanism" software package [1] are presented. Specifics of swinging due to the slope, the pit and the bump are shown. For a typical set of robot parameters, the results of numerical experiments for pits of approximately the largest admissible sizes in cases where the support surface is rotated around one axis, around two axes, and for different types of pits, deep and shallow. In all cases, there is a bump next to the pit.
The results of computer simulation testify to the fundamental feasibility of the proposed robot control algorithm, and develop the results presented in previous papers regarding the construction of algorithms for controlling robot behavior in extreme situations using computer experimentation methods. The algorithms proposed in this work were verified using computer simulation in a software environment implementing the computation of the interaction of the complete three-dimensional dynamic model of the system consisting of the robot interacting with the support [2-4]. The analytical analysis of a simplified dynamics of the system helped find constraints on the application of the proposed method due to geometric and mass characteristics of the robot design [4]. The specifics of swinging due to the slope, the pit and the bump were worked out using computer simulation and are presented.

References:
[1] Universal mechanism. Modeling the dynamics of mechanical systems, http://www.umlab.ru, last accessed: 2020/10/02.
[2] Golubev Yu.F., Koryanov V.V., Melkumova E.V. Rescue of the Walking Robot from an Emergency Position on the Back in the Presence of Interference. In the collection of 1st All-Russian Conference with International Participation "Biomechatronic Systems: Problems, Theory, Technologies". Proceedings, abstracts, pp. 9-12.
[3] Golubev Yu.F., Koryanov V.V., Melkumova E.V. Flipping the Walking Robot to the Working Position, 25th International Congress of Theoretical and Applied Mechanics, 22-27 August 2021. Abstract Book, Milano, Italy, pp. 2080-2081.
[4] Golubev Yu.F., Koryanov V.V., Melkumova E.V. Six-Legged Robot Overturn from an Emergency Position on the Back Under the Influence of Hindrance, Chugo D., Tokhi M.O., Silva M.F., Nakamura T., Goher K. (eds) Robotics for Sustainable Future. CLAWAR 2021. Lecture Notes in Networks and Systems, vol. 324, Springer Cham, pp. 192-202. DOI: 10.1007/978-3-030-86294-7_17.

STATISTICAL ANALYSIS OF CHAOTIC MOTIONS OF ONE VIBRO-IMPACT SYSTEM

Gorbikov S.P.[1], Menshenina A.V.[2]
1 - Nizhny Novgorod State University of Architecture and Civil Engineering, Nizhny Novgorod, Russia
2 - Volga State University of Water Transport, Nizhny Novgorod, Russia
gorby50@yandex.ru, alya112@yandex.ru

The report presents results of numerical research of vibro-impact system that describes [1] motion of the hanging on the spring weight hitting a fixed limiter. A bifurcation [2, 3] leading to chaos occurs in this system. There exists a periodic motion with a section of infinite-impact motions before the studied bifurcation. Here, an infinite-impact motion is understood as a motion with an infinite number of impacts over a finite period of time. The considered periodic motion arrives on the infinite-impact motions domain border at the bifurcation moment. After the bifurcation chaotic motions appear instead of the indicated periodic motion. These chaotic motions are explained by emergence [2, 3] of different Smale horseshoes after the bifurcation.
For the studied vibro-impact system parameter values of bifurcation are computed. Also Smale horseshoes and chaotic motions in their neighborhood are numerically observed after the bifurcation. Here, chaotic motions are understood as irregular motions with sensitive dependence on initial conditions.
Computational investigation of chaotic motions after the bifurcation indicates [4] that these chaotic motions have a limit set. Statistical analysis of the chaotic motions in small neighborhood of the considered limit set leads [4] to the following conclusions. Trajectories getting into a small neighborhood of the limit set do not leave it and show chaotic

behavior. Motions coming out of points of the limit set and of its neighborhood are chaotic. Also computations show that the specified limit set has the stirring property and the property that the time average coincides with the ensemble average.

References

1. Gorbikov, S.P., The main steady-state motions of the oscillator without viscous friction with a gap and a fixed limiter, *Vestn. Nizhegorod. gos. univ. ser. mat. mod. and opt. upr.*, N. Novgorod, 1998, no. 2(19), pp. 63-73.

2. Gorbikov, S.P., Menshenina, A.V., A new road to chaos in dynamic systems with impact interactions, *XXI International Congress of Theoretical and Applied Mechanics: summary*, *IUTAM*, 2004, ISBN 83-89697-01-1.

3. Gorbikov, S.P., Menshenina, A.V., Bifurcation leading to appearance of chaotic motions in dynamic systems with impact interactions, *Differents. Uravn.* 2005, vol. 41, no. 8, pp. 1046-1052.

4. Gorbikov, S.P., Menshenina, A.V., Statistical description of the limiting set for chaotic motions of a vibro-impact system, *Automation and Remote Control*, 2007, no. 10, pp. 70-78.

THIRD BODY EFFECT ON FRICTION AND WEAR IN ROLLING CONTACT

Meshcheryakova A.R.
Ishlinsky Institute for Problems in Mechanics RAS, Moscow, Russia
mif-almira@yandex.ru

In this study, the rolling contact of elastic bodies is considered in the presence of an intermediate layer, which is formed by wear particles, applied lubricant and possible surface contamination. The mechanical properties of the layer in normal and tangential directions are described by the one-dimensional Maxwell model. The materials of the rolling body and the base are assumed to be the same. The effect of the layer's properties and the conditions of contact interaction on contact normal and shear stresses, internal stress state of the elastic half-space and fatigue damage accumulation in cyclic loading conditions is studied.

Fatigue damage accumulation is modelled using the macroscopic approach, where the damage at the depth of an elastic half-space depends on the principal shear stress amplitudes, number of cycles and the initial damage. The fatigue crack is considered as initiated, when the value of the damage function becomes equal to the threshold value. To calculate the contact normal stresses distribution the strip method [1] is used. The contact region is divided into the thin strips, and for each strip the two-dimensional contact problem of rolling of elastic bodies in the presence of a viscoelastic layer is considered. The problem of contact shear stress determination is solved using the variational approach [2], which consists of the minimization of the functional, which is built taking into account the boundary conditions for stresses and displacements in the contact region. The components of the internal stress tensor within the elastic half-space are calculated using the principle of superposition and the Boussinesq and Cerruti solutions for the concentrated forces acting on the elastic half-space in normal and tangential directions [3].

The influence of the sliding friction coefficient, the relative slippage, and the properties of a viscoelastic layer on the distribution of shear stresses and the rate of damage accumulation are studied. The results show that the damage function has two maximums: on the surface of the elastic half-space and at a certain depth. The increase of the sliding friction coefficient or relative slippage leads to reaching the maximum value of the principal shear stress amplitude on the surface of the half-space, which results in contact fatigue surface fracture (wear). The results also demonstrate that the presence of a third body layer leads to a decrease of the principal shear stress amplitude within the elastic half-space.

The reported study was funded by RFBR and MOST, project number 21-58-52006.

1. Haines D.J., Ollerton E. Contact Stress Distributions on Elliptical Contact Surfaces Subjected to Radial and Tangential Forces // Proc. Inst. Mech. Eng. 1963. Vol. 177, № 1. P. 95–114.

2. Goldstein R.V. et al. Solutions of three-dimensional rolling problems with slip and adhesion by variational methods // Adv. Mech. 1982. Vol. 5, № 3/4. P. 61–102.

3. Johnson K.L. Contact Mechanics. Cambridge University Press, 1985.

MODELING A DETONATION ENGINE USING THE REDUCED KINETIC MECHANISM OF ACETYLENE

Mikhalchenko E.V., Nikitin V.F.
SRISA RAS
mikhalchenkolena@yandex.ru

Currently, the aerospace engine industry is addressing several promising areas of development. One of them is the use of detonation combustion of fuels. The expediency of transition to detonation combustion is mainly due to the higher efficiency of the thermodynamic cycle using detonation combustion. The main advantages of the detonation engine are a compact combustion chamber, short nozzles, high combustion efficiency and low concentrations of harmful substances. There are two main types of detonation engines: the pulse detonation engine (PDE) and the rotating detonation wave engine (RDE). The reason of switching to detonation combustion is mainly because of a higher efficiency of the thermodynamic cycle with detonation process. Currently, special attention is paid to the engine with a continuous detonation wave, this due to higher work frequencies and the possibility of a single initiation of the

detonation wave. There are three main geometries of a rotating detonation wave engine (RDE): an annular RDE, a hollow RDE, and a disk RDE. There are two configurations among RDEs with an internal body: with an annular chamber and with an elliptical combustion chamber, or racetrack RDE. In general, there are still many problems in the design of the RDE combustion chamber, such as detonation initiation, stability of detonation, mixing of fuel and oxidizer. Experimental and theoretical RDE studies are conducted all over the world.
The work considers three-dimensional modeling of a detonation combustion chamber with a continuous detonation wave on acetylene oxygen mixture. The geometric parameters of the chamber correspond to the experimental setup presented by Bykovsky and his collaborators. The diameter of the chamber is 10 cm, the length is 10 cm and the initial width of the channel is 0.5 cm. The effect of bridges in the area of mixture supply on the maintenance of the detonation wave is considered.
This work was supported by the subsidy of the Ministry of Science and Education of Russian Federation on the topic: "Investigation and development of detonation combustion chambers being used in perspective aerospace propulsion systems" (No. 075-15-2021-1385).

EQULIBRIUM ENSEMBLES OF MISFIT DISLOCATION LOOPS IN CORE-SHELL NANOPARTICLES WITH TRUNCATED SPHERICAL CORES

Mikheev D.S.[1], Kolesnikova A.L.[2,3], Gutkin M.Yu.[1,2,3], Romanov A.E.[2], Smirnov A.M.[2], Krasnitckii S.A.[1]
1 - Department of Mechanics and Control Processes, Peter the Great St. Petersburg Polytechnic University, Polytekhnicheskaya 29, St. Petersburg, 195251, Russia
2 - ITMO University, Kronverkskiy pr. 49, St. Petersburg, 197101, Russia
3 - Institute of Problems of Mechanical Engineering, Russian Academy of Sciences, Bolshoj 61, Vasil. Ostrov, St. Petersburg, 199178, Russia
ds.mikheev@mail.ru

The elaboration, investigation, and application of composite nanoparticles are extensive fields at the forefront of the development of modern nanotechnologies. In particular, of special interest are core-shell nanoparticles (CSNPs) [1-3]. The phase composition heterogeneity of CSNPs leads to the appearance of residual elastic strains and stresses caused by the lattice misfit and different thermal expansion coefficients of components. According to existing theoretical models [4, 5], different misfit stress relaxation mechanisms are possible in CSNPs, which include the formation of misfit dislocations (MDs) around the core, prismatic and glide dislocation loops in the shell, cracks in the core or shell, core-shell separation, and core displacement from the CSNP center. Approximate calculations [5] showed that the MD formation is energetically more favorable than cracking or core-shell separation. In recent years, a number of theoretical models have been suggested to calculate the critical conditions for the onset of MDs in CSNPs [5-8]. However, all these calculations were done for spherical CSNPs with centered spherical cores although in practice, CSNPs demonstrate rather different architectures [1-3]. Recently, the boundary-value problem in the theory of elasticity for an axisymmetric truncated spherical inclusion, arbitrary placed in an elastic sphere, has been solved and applied to the case of so-called Janus particles [9]. This solution is used in the present work which is aimed at the theoretical description of misfit stress relaxation by generation of circular prismatic loops of MDs in CSNPs with axisymmetric truncated spherical cores [10]. The special case of a semispherical core with base in the equatorial plane of the nanoparticle is considered and analyzed in detail. Relaxation of the residual stress was carried out due to the formation of a prismatic loop at the boundary of the core and shell. In this paper, the possibility of the formation of no one, but several dislocation loops interacting with each other is investigated. The interaction energy of such loops is known [11]. The results obtained show that with the growth of the discrepancy, the formation of an increasing number of loops is energetically advantageous. At the same time, nanoparticles in which the radius of the nucleus is 0.75 of the outer radius of the nanoparticle are the most unstable to the formation of mismatch dislocation loops.

References
[1] De Mello Donega C., Chem. Soc. Rev. 40 (2011) 1512.
[2] Zhang N., Liu S., Xu Y.J., Nanoscale 4 (2012) 2227.
[3] Liu X., Iocozzia J., Wang Y., Energy Environ. Sci. 10 (2017), 402.
[4] Trusov L.I., Tanakov M.Yu., Gryaznov V. G., et al., J. Cryst. Growth 114 (1991) 133.
[5] Gutkin M.Yu., Int. J. Eng. Sci. 61 (2012) 59.
[6] Gutkin M.Yu., Kolesnikova A.L., Krasnitckii S.A., et al., Phys. Solid State 56 (2014) 723; Scr. Mater. 83 (2014) 1.
[7] Gutkin M.Yu., Smirnov M.A., Phys. Solid State 56 (2014) 703; Acta Mater. 88 (2015) 91; Phys. Solid State 58 (2016) 1611.
[8] Gutkin M.Yu., Krasnitckii S.A., Smirnov M.A., et al., Phys. Solid State 57 (2015) 1177.
[9] Kolesnikova A.L., Gutkin M.Yu., Krasnitckii S.A., et al., Rev. Adv. Mater. Sci. 57 (2018) 246.
[10] Gutkin M.Yu., Kolesnikova A.L., Mikheev D.S., et al., Eur J Mech A Solids 85 (2020)
[11] Krasnitckii S.A., A.M. Smirnov., Gutkin M.Yu., Mat. Phys. and Mech. 44 116-124 (2020)

DEVELOPMENT OF VISCOELASTIC MODEL FOR ELASTOMERIC NANOCOMPOSITES

Mokhireva K.A., Svistkov A.L.
Institute of Continuous Media Mechanics of the Ural branch of the Russian Academy of Science, Perm, Russia
lyadovaka@icmm.ru

A differential model is proposed to describe the viscoelastic properties of polymer nanocomposites in experiments with complex loading history. It is known that the peculiarities of the mechanical behavior of filled elastomers are influenced by many factors (strain rate, cyclic loading conditions, etc.). To simplify the problem of model development, it is necessary to conduct such an experiment as a result of which it is possible to not take into account (Mullins softening effect) or vary (loading rates) factors which are significantly affects the material response. For this purpose, experiments with nested stress/strain cycles were performed on filled rubber specimens. It allowed to define the viscoelastic behavior of the softened material at different (but constant over each cycle) strain rates and also determine its elastic (equilibrium) behavior. Thus, the problem can be divided into two subtasks which consist of specifying the elastic potential to describe the equilibrium state and finding the components of the stress tensor responsible for dissipative processes in the material. In this study, the equation for determining the inelastic (dissipative) part of the stress tensor was refined. The proposed model was applied to describe the properties of filled polymer systems under uniaxial cyclic loading with different but constant in each cycle strain rates.
The reported study was funded by RFBR and Perm Territory, project number 20-41-590001 and the Ministry of Science and Higher Education of the Russian Federation (theme No. AAAA- A20-120022590044-7).

INFLUENCE OF HEAT EXCHANGE ON THE HYDRODYNAMICS PARAMETERS OF ANOMALOUS THERMOVISCOUS LIQUID FLOW IN AN ANNULAR CHANNEL

Mukhutdinova A.A.[1], Kireev V.N.[2], Urmancheev S.F.[1]
1 - Mavlyutov Institute of Mechanics, Ufa Investigation Center, R.A.S.,Ufa, Russia
2 - Bashkir State University,Ufa,Russia
muhutdinova18@gmail.com

Possible variations in the thermophysical properties of fluids can have a significant impact on the flow pattern and determine the performance of technical systems. The viscosity dependence on temperature, characteristic of most fluids, as a monotonically decreasing function can be violated for substances in which polymerisation and depolymerisation of molecules can occur within a limited temperature range. Such substances, for example, include polymer solutions and melts and liquid sulphur [1]. Thus, the theoretical investigation of the hydrodynamic and heat transfer processes involved in the flow of thermo-viscous fluids is extremely important.
In this paper, the flow of an anomalously thermo-viscous incompressible fluid in an annular channel, on the inner and outer surfaces of which different heat exchange conditions are set. The viscosity of the fluid depends on the temperature in a non-monotonic way. Mathematical model includes continuity, Navier-Stokes and energy conservation equations written in cylindrical coordinate system considering axial symmetry [2]. The equations of the mathematical model were solved numerically using the method of control volumes [3].
As a result of numerical modelling, the graphs of velocities in different cross-sections of the annulus, as well as distributions of temperature and viscosity fields in the flow area, have been got. The influence of geometric parameters of the annular channel, heat exchange conditions on its walls, and rheological parameters of the liquid on the flow character are established. It is shown that in a liquid with a non-monotone dependence of viscosity on temperature, the hydrodynamic parameters of the flow depend on the location of the region of high viscosity flow - the “viscous barrier”. The existence of different flow regimes depending on the heat exchange intensity is also found.
The study was supported by the Russian Science Foundation (Project No. 22-21-00915).
References
[1] Urmancheev, S. F. Steady flow of a fluid with an anomalous temperature dependence of viscosity // Doklady Physics. – 2004. – Vol. 49. – No 5. – P. 328-331.
[2] Bird, R. B., Armstrong, R. C., Hassager, O. Dynamics of Polymeric Fluids // Fluid Mechanics. – 1987. – Vol. 1. – P. 649.
[3] Patankar, S. Numerical Heat Transfer and Fluid Flow // New York: Hemisphere Publishing Corporation. – 1980. – P. 200.

THE INFLUENCE OF HYDRAULIC FRACTURE OPENING ON THE PATH OF ACOUSTIC WAVES

Nachev V.A., Zenchenko E.V., Zenchenko P.E., Turuntaev S.B.
Sadovsky Institute of Geosphere Dynamics of Russian Academy of Sciences, Moscow, Russia
nachev@phystech.edu

Hydraulic fracturing is the main method of intensifying hydrocarbon production, and its role increases with the transition to the development of hard-to-recover reserves, deposits in shale rocks, and Bazhenov and Domanik formations. The complexity of the technology of hydraulic fracturing imposes requirements for the complexity of the calculation models used in the planning and execution of works. Verification of the validity of the assumptions used in theoretical models is possible only by conducting controlled experiments under laboratory conditions. In these experiments, it is important to use measurement methods that do not affect the process under study, on the one hand, and allow you to get the maximum information, on the other hand. For several years, the team of authors has been conducting an experimental study of hydraulic fracturing on the original installation, which allows working under three-axis loading conditions on cylindrical samples with a sufficiently large diameter (430 mm) and a height of 70 mm. In the last experiments, we used ultrasonic transmission of samples during the formation of hydraulic fracturing and filling it with liquid.

The purpose of laboratory experiments was to study the dependence of the amplitude of the ultrasonic wave that passed through the fracture on the magnitude of its opening. Experiments were carried out in different types of model materials made on the basis of gypsum. In one case, a homogeneous material was used, in another case, the model material contained marble chips. In these experiments, a pre-formed circular hydraulic fracturing was used, the plane of which was perpendicular to the axis of the cylindrical sample. A cased injection well was located along the same axis, ending in the middle of its height. Along with laboratory experiments, numerical physical and mathematical modeling of the passage of elastic waves through fractures with the complete destruction of the material and filling with liquid was carried out.

Based on the results of laboratory experiments and numerical modeling, the dependences of the amplitude of the ultrasonic wave that passed through the fracture were constructed, depending on its disclosure for materials with different degrees of the roughness of the fracture surface. The results obtained will allow us to estimate the magnitude of the hydraulic fracturing opening in laboratory experiments conducted on larger samples using active acoustic monitoring.

NUMERICAL INVESTIGATION OF CYMBAL TRANSDUCER FROM POROUS PIEZOCERAMICS WITH METALLIZED PORE SURFACES

Nasedkin A.V.[1], Nasedkina A.A.[1], Nassar M.E.[1,2], Rajagopal A.[3]
1 - Southern Federal University, Rostov-on-Don, Russia
2 - Menoufia University, Menouf, Egypt
3 - Indian Institute of Technology, Hyderabad, India
nasedkin@math.sfedu.ru

Porous piezoceramic materials with enhanced exploitation characteristics are being actively developed in the recent years. So, the method of transportation of micro- and nanoparticles of various substances into piezoceramic materials was suggested. Application of this method enables to obtain porous piezoceramics inside which on the boundaries of the piezoceramic matrix with pores metal particles are deposited.

In the beginning we present the numerical results on the calculation of effective properties of such microporous piezoceramic materials. The investigation was based on a complex approach which included the effective moduli method for the mechanics of composites, modeling of representative volumes, finite element solution of the set of static electroelastic problems with special boundary conditions and postprocessing of the computation results. To simulate the metallization on the boundaries of pores we model the compound pores as the pores with additional layers which have very high dielectric constants. The results of the numerical experiments on solving the homogenization problems with the help of ANSYS finite element package enabled to estimate the influence of the metallization of the pore surfaces on the values of effective moduli of piezoelectric materials, which were obtained by the method of transportation of micro- or nanoparticles into ceramic matrices. We have found that the pore surface metallization significantly increases the effective transverse piezoelectric modulus, which seems promising for the use of this piezocomposite in a cymbal transducer.

Then we analyze the cymbal transducer with piezoelectric disk made from different variants of PZT ceramics: dense piezoceramics, ordinary porous piezoceramics, porous piezoceramics with porous boundaries covered by infinitely thin layer of metal, and porous piezoceramics with porous boundaries covered by metalized layer with sufficiently great thickness. For every case for material of piezoelectric disk we accept the suitable effective material moduli of porous PZT ceramics obtained previously.

Next, solid and finite element models of the considered cymbal transducer were constructed in an axisymmetric formulation. Developed programs for ANSYS software allowed to calculate the first's electrically active resonance frequencies and to carry out the harmonic analysis of axial and radial vibrations of transducer near to resonance

frequencies. The computational results have shown that the axial vibrations on the first electrically active resonance frequency are largest for the cymbal transducer made from porous piezoceramics with porous boundaries covered by infinitely thin layer of metal. Thus, we can conclude that microporous piezoceramics with metalized pore surfaces has perspective properties for practical use.
The first three authors acknowledge the support of the Russian Science Foundation, grant No. 22-11-00302.

VIBRATIONS OF A CYLINDRICAL SHELL WITH THE END PLATE

Filippov S.B., Smirnov A.L., Nesterchuk G.A.
St Petersburg University, St Petersburg, Russia
grigory_ne@mail.ru

Low-frequencies of a structure consisting of a closed circular cylindrical shell with the circular end plate are obtained by means of numerical and asymptotic methods. Three types of vibrations are analyzed.
Eigenfrequencies of the first type are close to frequencies of a plate with the clamped edge. The corresponding modes mainly cover the plate while the cylindrical shell stays untouched. The first asymptotic approximation of solution of a clamped plate vibrations equation well agrees with numerical results obtained by means of FEA with COMSOL package. The relative error of the second approximation found with the help of asymptotic method developed in [1] does not exceed 2%.
Vibration frequencies of the second type slightly differ from vibration frequencies of a cylindrical shell. To find those frequencies we seek solutions of thin shells theory equations in the form of a sum of slowly varying functions and edge effect integrals [2]. The asymptotic formula gives a good estimate for frequencies at sufficiently large wavenumbers.
In the approximate analysis the third type vibrations of the structure may be considered as vibrations of the beam with circular cross-sectional area. For sufficiently large shell lengths, the error of the approximate analytical solution doesn't exceed 5%.
Two optimization problems are considered. In the first one, for a structure with the given mass, the optimal ratio of the plate thickness and shell thickness, which provides the maximum value of the fundamental eigenfrequency, is found. In the second two-parametric problem, for a structure with the given mass, the radius of curvature of the plate and the ratio of the thicknesses of the plate and the shell are the optimization parameters. Increasing the curvature of the plate with a simultaneous decrease of its thickness and, accordingly, an increase of the thickness of the shell, it is possible to make the first eigenfrequency of the entire structure higher.

References
[1] *Filippov, S.B*. Asymptotic approximations for frequencies and vibration modes of cylindrical shell stiffened by annular plates. In: Analysis of Shells, Plates, and Beams. A State of the Art Report, Springer's Series Advanced Structured Materials, Vol. 123, 123-140, (2020).
[2] *Filippov, S.B.* Optimal Design of Stiffened Cylindrical Shells Based on an Asymptotic Approach. In: Technische Mechanik, Band. 24, Heft 3-4, 221-230, (2004)

SIMULATION OF ELASTIC GUIDED WAVE SCATTERING BY LOCALIZED OBSTACLES WITH 1D ENGINEERING MODELS

Nets P.A., Eremin A.A.
Kuban State University, Institute for Mathematics Mechanics and Informatics, Krasnodar, Russia
polina.nec@mail.ru

The study of guided wave interaction with localized obstacles in layered elastic structures is among the prior tasks in ultrasonic non-destructive testing and active structural health monitoring. Along with the models based on the complete system of elastodynamic equations, the scattering of normal modes by certain types of defects can be modeled within the framework of simplified 1D approaches. Combining the physical clarity of the resulting solution with computational efficiency, they allow a detailed parametric analysis of the corresponding wave phenomena. Thus, it is of particular interest to estimate the frequency ranges in which such simplified models adequately describe the scattering process.
In the current work, guided wave scattering by rectangular notches and strip-like horizontal cracks is considered. Such types of obstacles are widely studied in the problems of ultrasonic nondestructive testing as the simplest models of pitting corrosion damage or fatigue crack, correspondingly. The developed computational models rely on approximate plate theories of increasing complexity, namely, Poisson theory for in-plane motion and Kirchhoff and Mindlin theories for flexural vibrations. The main factor for the correct analysis of wave processes related to the scattering of incident guided waves by these defects with 1D models is the correct formulation of boundary conditions at the junction points of waveguides of different thicknesses (E. Glushkov, et al. *Low-cost simulation of guided wave propagation in notched plate-like structures*, J. Sound and Vibration, 352 (2015)).
With the implemented computational models, power transmission and reflection coefficients are analyzed with respect to variation of geometrical parameters of the considered obstacles. As the reference solution for the validation of the developed models and the estimation of frequency ranges of their applicability, a numerical hybrid scheme relying on

the complete 2D plain-strain statement is employed (E. Glushkov, et.al., Acoust. Phys., 2018, 64(1)). When analyzing the propagation of fundamental antisymmetric A0 and symmetric S0 modes through a notched or cracked waveguide, the possibility of an adequate description of wave energy transmission/reflection coefficient behavior is confirmed in the range below the half of the first cut-off frequency. Moreover, resonance phenomena typical for deep rectangular notches are reliably described with 1D models as well. In the case of a strip-like crack, however, only resonance motion initiated by the incident A0 mode could be observed, while, in contrast to the complete 2D statement, the scattering of S0 mode does not result in any resonance phenomena.
The work is supported by the state assignment of the Ministry of Science and Higher Education of the Russian Federation (Project No FZEN-2020-0017).

MOLECULAR DYNAMICS SIMULATION OF GRAIN DEFORMATION IN ALUMINUM BRONZE UNDER SHEAR LIMITING CONDITIONS

Nikonov A.Yu., Lychagin D.V., Bibko A.A.
Institute of Strength Physics and Materials Science SB RAS, Tomsk, Russia
anickonoff@ispms.ru

Molecular dynamics modeling allows us to consider the motion and interaction of dislocations in crystal structures. Modeling of the deformation of crystals of aluminum bronze was carried out using the LAMMPS software package and the interatomic potential constructed in the framework of the embedded atom method. The nucleation and development of a defect structure in the samples under uniaxial compression was studied. The effect of limiting shear towards one or more lateral surfaces was considered. It is shown that shear blocking leads to shear selectivity in sliding systems that provide the required shape change. Based on the simulation results, the relationship between strain curves and structural characteristics is traced. A higher degree of hardening and density of defects during deformation in constrained conditions was established. The results of modeling the deformation of a polycrystal fragment showed a qualitative agreement with the results obtained during the experiment.
This research was funded by the Research Program 20-72-10184 of the Russian Science Foundation for 2020–2023.

INVESTIGATION OF THE BACK-STRESS IMPACT ON THE BREAKDOWN PRESSURE OF THE HYDRAULIC FRACTURE

Novikova E.V., Trimonova M.A.
Sadovsky Institute of Geosphere Dynamics of Russian Academy of Sciences
helenvn97@gmail.com

Hydraulic fracturing is one of the most common methods of studying the stress-strain state of the reservoir being developed. To form a hydraulic fracture, the fracturing fluid is injected under pressure into the oil reservoir under development through a specially drilled well. The formed fracture is of interest to the researcher, as it allows to estimate the values of the main stresses acting in the undeformed formation. However, the process of initiation and further fracture propagation is affected not only by the initial stress field in the rock and the tensile strength of the rock, but also by the rupture fluid that is pumped through the borehole. This fluid is filtered through the walls of the well into the surrounding formation, which on the one hand contributes to the opening of the fracture, and on the other hand hinders due to the resulting back-stress effect. The so-called reverse stress effect (back-stress effect) describes the occurrence of additional stress on the walls of the well from the reservoir due to the rupture fluid that has filtered out of the well into the reservoir. The purpose of this work was to determine the effect of the reverse stress effect on the breakdown pressure of the fracture. There are various methods for determining the main stresses acting in the formation and some parameters characterizing the fracture, such as fracture breakdown pressure, length and width of the fracture and fracture closure pressure. One of the most common methods is the method of analyzing the dependencies of borehole pressure on time. In the course of this work, the analysis of such borehole data was carried out, which were obtained during a series of laboratory experiments on hydraulic fracturing. The experiments were carried out on a special laboratory installation that allows you to create loading conditions on a model sample that are close to conditions at a real field being developed.

HYBRID MODELING OF GAS-DYNAMIC PROCESSES IN AC PLASMA TORCHES

Obraztsov N.V.[1,2], Bykov N.Y.[1,2], Hvatov A.A.[1], Maslyaev M.A.[1], Surov A.V.[1,3]
1 - ITMO University, St. Petersburg, Russia
2 - Peter the Great St. Petersburg Polytechnic University, St.Petersburg, Russia
3 - IEE RAS, St. Petersburg, Russia
obraztsovnikita@yandex.ru

Modeling the flow of plasma-forming gas in an AC plasma torch is a complex interdisciplinary problem [1-4]. It is necessary to take into account interrelated non-stationary gas-dynamic, thermal and electromagnetic processes. From the point of view of the flow pattern, it is important to take into account the movement of the arc attachment spot along the electrode. The time-dependent function of arc motion in the near-electrode space can be determined by the generative model design (GDM) method based on available experimental data. The paper discusses a hybrid model that includes the equation of motion of the attachment spot reconstructed using the GDM method, integrated into the general model of the flow of an electrically conductive gas in an alternating electric field. In turn, the gas motion model also has a number of features. Despite the low velocity of the medium, energy release into the flow requires consideration of the compressibility factor. Within the framework of the Comsol Multiphysics^R package used, simulation of compressible gas flows is possible within several approximations. These approximations are determined depending on the values of the operation parameters and the type of plasma torch. The paper discusses the features of modeling compressible gas flows within the framework of the hybrid model under consideration in the Comsol Multiphysics^R environment.
This research is financially supported by The Russian Science Foundation, Agreement №21-11-00296, https://rscf.ru/en/project/21-11-00296/

[1] Sen-Hui Liu et al 2019 J. Phys. D: Appl. Phys. **52** 335203
[2] Xu ZHOU et al 2021 Plasma Sci. Technol. **23** 125405
[3] N. Y. Bykov, N. V. Obraztsov, A. A. Kobelev and A. V. Surov 2021 IEEE Transactions on Plasma Science **49** 1017-1022
[4] N. Y. Bykov, N. V. Obraztsov, A. A. Kobelev and A. V. Surov 2021 IEEE Transactions on Plasma Science **49** 1023-1027

RESEARCH OF UPWARD GAS-LIQUID FLOWS WITH FORMING AGENT IN A VERTICAL CHANNEL

Ogai V.A.[1], Musakaev N.G.[1,2], Borodin S.L.[1,2]
1 - Industrial University of Tyumen, Tyumen, Russia
2 - Tyumen Branch of Khristianovich Institute of Theoretical and Applied Mechanics of SB RAS, Tyumen, Russia
ogayvlad@mail.ru

Currently, in a number of natural gas fields, there are problems associated with the accumulation of water at the wells bottom. This phenomenon is often caused by the fact that due to the extraction of gas from a reservoir, the reservoir pressure is significantly reduced. In this regard, water from aquifers can percolate to the gas-saturated reservoir part. Therefore, the volumetric water content in the wellbore gas-liquid flow increases. This leads to an increase in the density of the two-phase mixture and an increase in hydraulic resistance. Accordingly, the flow rate of the well decreases (with a constant bottomhole pressure), and with a large flow of water, the well may be shutdown.
For the stable operation of wells at a late stage of gas field development, various measures are used. One of the effective ways to struggle the accumulation of water in gas wells is the supply of foam concentrates based on surface- active substances (SAS) to the wells bottom. This technology has a relatively low volume of capital investments and high efficiency. When SAS is fed to the well bottom, foam is formed, which leads to decrease in the density of the gas-liquid mixture and the coefficient of surface tension between the liquid and gas decreases. As a result, the critical gas velocity required to lift the fluid along the wellbore decreases, which allows the well to be operated without replacing the lifting string with a pipe of a smaller diameter and/or increasing the flow rate of the produced fluid. Since the technology of operation of gas wells with the use of SAS is becoming more and more spread, it is relevant to research the upward gas-liquid flows, which will make it possible to find the distributions of the main parameters along the well height for various operating modes.
This work presents a technique for studying gas-liquid flows with SAS in a vertical channel at various pressures. On the experimental stand simulating a section of a gas wellbore, data were obtained on the parameters of stationary flows of gas-liquid mixtures with various types of aqueous surfactant solutions (type of surfactant and its concentration in solution), different pressure values (up to 1 MPa), and different volumetric air flow rates. Based on the equations of the multiphase media mechanics, a mathematical model of the processes occurring during the movement of a gas-liquid mixture with surfactants in a gas wellbore is proposed.
The research was funded by RFBR and Tyumen Region, project number 20-41-720002.

ANALYSIS OF MECHANICAL HYSTERESIS LOOPS OF FIBER-REINFORCED COMPOSITES BASED ON POLYIMIDES BY THE DIC METHOD

Panin S.V.[1,2], Bogdanov A.A.[1,2], Lyubutin P.S.[1], Eremin A.V.[1,2], Buslovich D.G.[1], Byakov A.V.[1]
1 - Institute of Strength Physics and Materials Sciences SB RAS, Tomsk, Russia
2 - National Research Tomsk Polytechnic University, Tomsk, Russia
svp@ispms.ru

On the basis of a servo-hydraulic testing machine and an optical system for strain measurement according to the DIC principle, a laboratory set up was designed for studying the processes of fatigue of polymers and polymer composites using the parameters of mechanical hysteresis loops. Load data logging is based on the hardware readings of the Biss machine (Bangalore, India) force meter. Deformation was assessed by the optical method within the gauge-length of the sample. In order to reduce the influence of noise and interferences, software approximation of the load-deformation data has been implemented. It is shown that the strain values calculated from the data of the optical method are effectively approximated by the global B-spline function.
To assess the degradation of strength properties during cyclic tests, the following parameters of mechanical hysteresis loops were used: dynamic and secant moduli, as well as the area of the hysteresis loop. The properties of composites under low-cycle fatigue (up to 10^4 cycles) reinforced with 10 wt. % of short carbon fibers of two types: carbonized (CCF) and graphitized (GCF) were studied in this work. It was found that the composite reinforced with CCF fibers has an order of magnitude greater durability than those with GCF ones. This was related to the parameters of the loops, mainly in the secant modulus, the decrease of which by the time of failure was 400 MPa for CCF and 200 MPa for GCF. Thus, the DIC method and loop parameters are informative parameters for estimating property degradation of polymer composites under fatigue.

A COMPUTER SOFTWARE PACKAGE FOR SAND PRODUCTION MODELLING

Pashkin V.D.
Peter the Great St. Petersburg Polytechnic University, Saint Petersburg, Russia
pashkin.vd@edu.spbstu.ru

Sand production is often observed during the development of weakly consolidated reservoirs. This process might lead to economical loss resulted from different problems such as frequent borehole cleanout and damage of submersible equipment. However, there is a lack of computational methods for sand processes evaluation. The article deals with the problem of development of software package for mathematical modelling of sand production. Software package is PyQt application designed to solve failure problem and sand transport problem. Mathematical model of failure is based on the erosion theory and Mohr-Coulomb criterion whereas sand transport is described in terms of mass balance equation. Finite-difference method is used as numerical method in software. It should be noted that coupling of failure process and sand transport in well is also taken into account. It is shown that proposed solution allows to determine the dynamics of sand production and predict the period of the well operation before the wellbore is filled with solid particles.

EFFECTIVE DIFFUSIVITY OF A POLYCRYSTALLINE MATERIAL WITH ELLIPSOIDAL INHOMOGENEITIES

Pashkovsky D.M.[1], Frolova K.P.[2], Vilchevskaya E.N.[2]
1 - Peter the Great St.Petersburg Polytechnic University
2 - Institute for Problems in Mechanical Engineering RAS, V.O., Bolshoj pr., 61, St. Petersburg 199178, Russia
mr.vivivilka@icloud.com

Impurity concentration during diffusion in inhomogeneous materials is not a continuous function at the interface between material matrix and inhomogeneities. This is often ignored when determining effective diffusivity. At the boundary between the matrix and the inhomogenity, the discontinuity of the concentration appears due to the accumulation of the diffusing substance inside or outside the inhomogeneities. This phenomenon is called the segregation effect.
The aim of this work is to compare two approaches to calculate the effective diffusivity of a polycrystalline material while taking into account the segregation effect. In the first approach, the grains are modeled by inhomogeneities, and the grain boundary is modeled by the material matrix. However, in the second approach, the grain boundary is modeled by inhomogeneities, and the grains are modeled by the material matrix. One needs to build an effective diffusivity tensor in order to compare these approaches. From a mathematical point of view, the difference between these approaches lies in the values of the micro-structural parameters included in the expression for this tensor.
The effective diffusivity tensor is a solution of the homogenization problem, when the inhomogeneous material transitions to a homogeneous with anisotropic properties. Also, we have to take into account the influence of inhomogenetics on each other because it is necessary for large volumes of inhomogenities fractions. To do this, we used

the Mori-Tanaka scheme. In this scheme, each of the isolated inhomogeneities is placed in a uniform field of a concentration gradient equal to the average of the material matrix. The effective diffusivity tensor depends on the generalized microstructural parameters: the volume fraction of inhomogeneities; the segregation factor; the shape factor of inhomogeneities; and the orientation spread factor.
After comparing the approaches, the first comparison approximates the experimental data better than the second one. The influence of the segregation effect on effective diffusion must be taken into account.

SOLVING OF PROBLEM OF THE GRIFFITH CRACK PROPAGATION BASED ON EQUATIONS OF NONLINEAR MODEL

Bulygin A.N., Pavlov Yu.V.
Institute of Problems in Mechanical Engineering of the Russian Academy of Sciences
yuri.pavlov@mail.ru

On the basis of a nonlinear model of deformation of a crystalline medium with a complex lattice [1,2], the problem of stationary propagation of the Griffith crack under the influence of uniform expanding stresses was set and solved. It is shown that the stressed and deformed states of the medium are determined both by external influences on the medium and by gradients of the optical mode (mutual displacement of atoms). Using the found general solutions of the dynamic equations of the nonlinear plane deformation model [3,4] the contributions from these factors are separated. Finding the components of the stress tensor and the macro-displacement vector is reduced to solving Riemann-Hilbert boundary problems. Their exact analytical solutions have been obtained. Analysis of the obtained results was carried out and comparison of calculations on a nonlinear model and a classical linear model was given.

References
[1] E.L. Aero. Microscale deformations in a two-dimensional lattice: structural transitions and bifurcations at critical shear. *Physics of the Solid State*, **42**, 1147–1153 (2000).
[2] E.L. Aero. Micromechanics of a double continuum in a model of a medium with variable periodic structure. *Journal of Engineering Mathematics*, **55**, 81-95 (2006).
[3] E.L. Aero, A.N. Bulygin, Yu.V. Pavlov. Nonlinear model of deformation of crystalline media allowing for martensitic transformations: plane deformation. *Mechanics of Solids*, **54**, 797–806 (2019).
[4] A.N. Bulygin, Yu.V. Pavlov. Solution of dynamic equations of plane deformation for nonlinear model of complex crystal lattice. *Advanced Structured Materials, **164**, Mechanics and Control of Solids and Structures,* V.A.Polyanskiy, A.K.Belyaev (eds.), Springer, Cham, Switzerland, 115-136 (2022).

INVESTIGATION OF THE MUTUAL INFLUENCE OF DIFFERENTLY LOCATED GROWING CRACKS

Pestov D.A.[1], Shamina A.A.[2], Zvyagin A.V.[2]
1 - Federal Science Center Scientific Research Institute of System Analysis of the Russian Academy of Sciences, Russia, Moscow
2 - Moscow M.V. Lomonosov State University, Russia, Moscow
dmitr-ey94@mail.ru

The presence and growth of cracks is one of the main reasons for the decrease of durability of solids. This can be both detrimental as in the case of cracks in structural materials leading to failure, or beneficial as in the case of hydraulic fracturing, where the formation's permeability and conductivity are thus increased. In both cases, this process requires study in order to effectively notice and prevent or manage it. One of the important aspects of this problem is the interaction of cracks with each other. This work presents a study of the mutual influence of two cracks at different locations, including the case of their growth.
To model this process, the following methods were used: the three-dimensional boundary-element method of discontinuous displacements developed by the authors, in which the field of stresses and displacements is a finite series of decompositions of analytically found functions, as well as the two-dimensional method of discontinuous displacements, which takes into account the turning of the growing crack according to the stress field at the tip with an adaptively refined mesh in the tip area in order to increase the accuracy of the calculation with a small loss of performance.
Calculations were carried out for two cracks located in parallel planes, with different distances between the planes and different distances between the projections of crack centers. The influence coefficient (the ratio of stress intensity factors for a fracture system to the corresponding value for a single crack of the same size) and the final shape of the crack in the case of growth were studied. The results showed that the coefficient of influence is less than unity in the case when the considered fracture is in the “shadow” of another fracture and is greater than unity in other cases. In this case, the influence coefficient is greatest if the projections of cracks are close to intersection, but have not yet intersected. It is also worth noting that during the growth of initially parallel cracks, they either deviate from each other if they are initially coaxial, or approach each other if the “shadow” area is small, or initially deviate from each other, and then approach each other if projections are close to crossing. Accounting for crack turning also has a significant

effect on the influence coefficient: for non-planar crack growth, the influence coefficient turns out to be larger or decreases more slowly than in the case of flat growth.

The present research was supported by the Russian Foundation for Basic Research (grant № 19-29-09070 mk).

EDGE DISLOCATION IN ELASTIC SPHERE

Petrov D.A.[1], Gutkin M.Yu.[1,2,3], Kolesnikova A.L.[2,3], Romanov A.E.[2]
1 - Peter the Great St. Petersburg Polytechnic University, St. Petersburg, Russia
2 - ITMO University, St. Petersburg, Russia
3 - Institute of Problems of Mechanical Engineering, Russian Academy of Sciences, St. Petersburg, Russia
petrov3.da@edu.spbstu.ru

Crystalline defects, particularly dislocations, emerge in heterogeneous equiaxed nanoparticles as result of relaxation processes and can lead to degradation of functional properties of the nanoparticles. A necessary step in studying the conditions for generation of defects is the analysis of their elastic fields. However, getting an analytical solution even for elastically isotropic spherical systems usually involves great mathematical challenges. Nowadays there are strict analytical solutions of boundary-value problems in the theory of elasticity for screw dislocations [1-3] and wedge disclinations [4,5] piercing solid and hollow spheres, twist disclination loops in solid spheres [3,6], prismatic dislocation loops in solid and hollow spheres [7,8], Marks-Ioffe stereodisclination in solid sphere [9], and ring Somigliana dislocation in solid sphere [10].

In the present work, an analytical solution to the boundary-value problem of a straight edge dislocation axially piercing an elastically-isotropic solid sphere is found for the first time. The solution is given by the sum of the well-known stress fields of the dislocation placed in an infinite elastic medium and the image stress fields caused by the presence of the sphere free surface. To get the second term, a classical method of solving the boundary-value problems in elastic sphere is used. It is based on the Trefftz representation of the displacement vector and implies finding vector and scalar harmonic functions. Here these functions are found and expressed analytically in terms of infinite series with Legendre and associated Legendre polynomials. The results are visualized with stress-field maps in different cross sections of the sphere. It is shown that the free surface significantly changes the stress fields with respect to the infinite case and introduces the following new features: the anti-plane shear stress components, the change of the stress sign near the surface, new singularities at the points where the dislocation crosses the surface. The dislocation strain energy in the system is also provided. The results of this work can be a basis for theoretical modelling the mechanisms of stress relaxation in equiaxed nanoparticles with planar inner interfaces.

[1] I.A. Polonsky, A.E. Romanov, V.G. Gryaznov et al., Czech. J. Phys. 41 (1991) 1249.
[2] A.L. Kolesnikova, A.E. Romanov, Int. J. Sol. Struct. 47 (2010) 58.
[3] A.L. Kolesnikova, M.Yu. Gutkin, A.E. Romanov, Rev. Adv. Mater. Sci. 55 (2018) 102.
[4] I.A. Polonsky, A.E. Romanov, V.G. Gryaznov et al., Philos. Mag. A 64 (1991) 281.
[5] A.L. Kolesnikova, M.Yu. Gutkin, A.V. Proskura et al., Int. J. Sol. Struct. 99 (2016) 82.
[6] A.L. Kolesnikova, A.E. Romanov, Tech. Phys. Lett. 35 (2009) 985.
[7] A.L. Kolesnikova, M.Yu. Gutkin, S.A. Krasnitckii et al., Int. J. Sol. Struct. 50 (2013) 1839.
[8] J.R. Willis, B. Bullough, A.M. Stoneham, Philos. Mag. A 48 (1983) 95.
[9] A. Howie, L.D. Marks, Phil. Mag. A 49 (1984) 95.
[10] D.S. Mikheev, M.Yu. Gutkin, A.L. Kolesnikova et al., In: Proc. of the XXII St. Petersburg Readings of Strength Problems, St. Petersburg, 2016, p. 269 (in Russian).

HEAT-FLUX DEFINITION REVISITED AND NONLINEAR TEMPERATURE-PROFILES IN ONE DIMENSIONAL SYSTEMS

Politi A.
University of Aberdeen, Aberdeen, UK
a.politi@abdn.ac.uk

A much-used definition of heat-flux turns out to be inaccurate at the microscopic level. I show that one can get rid of the inconsistency by decomposing the flux into a convective and a conductive component: their ratio is an indicator of gas-versus fluid-like behavior. Additionally, I revisit a linear stochastic model with conserved noise, deriving an analytic expression of the nonlinear temperature-profile and discussing a relationship with Levy walks.

PERFORMANCE ASSESSMENT OF A NEWLY DEVELOPED SOLVER FOR PFEM-2 METHOD FOR INCOMPRESSIBLE FLOW SIMULATION

Popov A.Yu.
Bauman Moscow State Technical University, Moscow, Russia
andreyypopov@bmstu.ru

Particle Finite Element Method, 2-nd generation (PFEM-2), is a contemporary method for solution of incompressible Navier-Stokes equations. Being a hybrid Eulerian-Lagrangian approach, this method is shown to be especially effective in case of convection-dominated flows. Scope of its application includes simulation of multiphase flows, free-surface flows, fluid-structure interaction problems and it seems to be suitable (according to the latest results of the method developers) for pseudo-direct simulation of high-Reynolds flows. Main advantage of the PFEM-2 follows from utilization of a set of Lagrangian particles, which provide subgrid scale resolution. The particles are transferred along the velocity streamlines and by this simulate convection. Other terms of the governing equations are resolved on a fixed Eulerian mesh by conventional finite element method. In case of convection-dominated flows the mesh is allowed to be relatively coarse. Furthermore, a larger time step can be used for transient problems.
The PFEM-2 was first proposed in 2013 and for a prolonged period of time only one software implementation was available publicly – in the framework of the KRATOS package. An alternative solver has been implemented by the authors within an open-source framework. The latter is based on the deal.II finite element method library. The solver can be run in parallel mode using MPI. This implementation was validated on a set of two-dimensional benchmarks.
In the present talk we demonstrate the comparison of performance of this solver against the OpenFOAM solver (which uses the conventional finite volume method). Two test cases were considered: the flow around a circular cylinder as well as the widely used model problem for a flow past NACA-0012 airfoil. Both cases are two-dimensional, the fluid is considered incompressible and the flow is laminar. We also present the assessment of efficiency of parallelization for these two software codes.

APPLYING OF NUMERICAL-ANALYTICAL METHODS TO CALCULATE THE PRESSURE FIELD IN A HETEROGENEOUS RESERVOIR

Yudin E.V.[1], Poroshin I.O.[2], Gruzdev I.E.[2]
1 - Gazpromneft-NTC
2 - Peter the Great St.Petersburg Polytechnic University
poroshin_io@mail.ru

As a rule, the basis for engineering calculations for monitoring of well productivity is models of stationary and non-stationary inflow in homogeneous reservoirs, or reservoirs with a given type of zonal heterogeneity. This is due to the availability of analytical models for these cases, which have a high calculation speed. In this paper, we propose approaches for using numerical-asymptotic methods to calculate a reservoir with arbitrary parameters: the location of sources, the distribution of heterogeneity, and the geometry and reservoir properties. This approach enables the development of an engineering tool in which, as the boundary conditions change in subsequent runs, the calculation can be completed in a short amount of time.
The main goal of this work is to develop a methodology for calculating the productivity of wells and fractures and pressure distribution in heterogeneous reservoirs, as well as calculating the mutual influence of sources. The developed approach allows solving stationary and non-stationary diffusion problems. A distinctive feature of the algorithm is the use of a dynamic mutual productivity matrix, which makes it possible to evaluate the influence of sources at each time step.

NONLINEAR STRAIN SOLITARY WAVES IN A METAMATERIAL

Porubov A.
IPME RAS, Saint Petersburg Russia
pav@ipme.ru

The nonlinear strain solitary waves in a metamaterial mass-in-mass lattice model are studied in the continuum limit. The main feature of the model is in the presence of the masses attached to the masses of the main chain giving rise to the coupling between the movement of the masses. An asymptotic procedure is developed to decouple the governing continuum equations and obtain the single equation for longitudinal strains. Analytical and numerical solutions of the equation reveal an influence of the nonlinearity of the metamaterial model and the attached mass ton the type of strain waves localization and the number of generated localized waves. This, in turn, suggests an improvement of the model by an inclusion of a switch-on/off of the attached masses to provide a control of a nonlinear strain wave localization in the metamaterial.

THE ROLE OF THE ANGULAR MOMENTUM IN KINETIC PROBLEMS

Prozorova E.V.
St. Petersburg State University, Russia
e.prozorova@spbu.ru

The main laws in physics and mechanics are the laws of conservation of mass, momentum, energy, angular momentum, charge, and some others. In our opinion, insufficient attention is paid to the law of conservation of angular momentum. In the report it is shown that the sum of the forces is insufficient for a complete description of the interacting particles. Any redistribution of particles is accompanied by the emergence of collective effects, which is associated with the action of the angular momentum (angular momentum) and, consequently, with the action of an additional force.
Lack of attention to the impact of the angular momentum and of boundary conditions in mathematical study of equations leads to the inadequacy of mathematical models to real processes.
This is how the apparatus of group methods, Hamiltonian formalism, kinetic theory and other theories were developed. However, the boundary conditions significantly change the properties of systems from the point of view of reversibility and ergodicity. For the Liouville equation, the problem of the special role of flows through the boundary and their directions arises. The paper discusses issues related to the formation of the structure of a continuous medium and the property of dissipativity, which are determined, among other things, by the boundary conditions and angular momentum.

1. Evelina Prozorova Influence of the Angular Momentum in Problems Continuum Mechanics WSEAS Transactions on Applied and Theoretical Mechanics ISSN: 1991-8747, E-ISSN: 2224-3429, Volume 16, 2021.
2. Evelina V. Prozorova. Influence of discrete model on derivatives in kinetic theory. JP Journal of Heat and Mass Transfer Volume 17, Number 1, 2019, Pages 1-19 ISSN: 0973-5763
3. Evelina Prozorova. The Effect of Angular Momentum and Ostrogradsky-Gauss Theorem in the Equations of Mechanics .WSEAS TRANSACTIONS on FLUID MECHANICS DOI: 10.37394/232013.2020.15.2
4. Evelina Prozorova. Influence of angular momentum and dimension on dynamics in mechanics WSEAS TRANSACTIONS on APPLIED and THEORETICAL MECHANICS DOI: 10.37394/232011.2021.16.1
5. Evelina Prozorova. Mechanism of Formation for Fluctuation Phenomena. Proceeding conference CHAOC-20 pp.729-736 http://www.cmsim.org/chaos2021.html

NONLINEAR NATURE OF THE YOUNG'S MODULUS OF ROCKS UNDER DYNAMIC LOADING: EXPERIMENTAL STUDIES

Riabokon E.P., Turbakov M.S., Kozhevnikov E.V., Poplygin V.V., Guzev M.A.
Perm National Research Polytechnic University
riabokon.evgenii@gmail.com

Experimental studies of the Young's modulus of sedimentary rock under dynamic loading are carried out. Before the start of the test, the rock sample was preloaded, which ensured the closure of microstructures in the rock and transferred the sample to a state of linear elasticity. The following dynamic loading test program included 9 modes. In each mode, a rock sample was loaded with frequencies from 0.1 to 60 Hz. The dynamic Young's modulus was determined using dynamic mechanical analysis with help of an electrodynamic testing machine and specialized software. The nonlinear nature of Young's modulus is revealed. With an increase in the frequency of the external load from 0.1 to 10 Hz and from 10 to 60 Hz applied to the rock sample, the Young's modulus first increases according to a logarithmic law, and then according to a power law. As the strain rate increases, the strain amplitude decreases. It is supposed that with an increase in strain rate, the rock becomes more rigid. The support of the Russian Science Foundation is gratefully acknowledged (Project No. 22-19-00447, https://rscf.ru/project/22-19-00447/).

DISCLINATIONS: FROM ELASTICITY TO APPLICATIONS

Romanov A.E.[1], Kolesnikova A.L.[2]
1 - ITMO University / Ioffe Institute RAS, Saint Petersburg, Russia
2 - IPME RAS, Saint Petersburg, Russia
alexey.romanov@niuitmo.ru

We present up-to-date information on the analytical solutions of isotropic elasticity boundary-value problems for disclinations – defects of rotational type in solids [1]. The considered plane elasticity problems include those for wedge disclinations in uniform or two-phase cylinders, at a free surface of a half-space, and in a plate of finite thickness [2]. Three-dimensional problems under analysis deal with wedge disclinations in a bulk sphere or spherical layer or with the defects with the lines being normal to a free surface of a half-space or to surfaces of the plate [2]. Possible applications of the elasticity solutions for wedge disclinations are discussed [1,2]. We demonstrate that the disclination properties become a controlling factor when considering rotational plasticity in solids [3], grain boundaries and their junctions in conventional polycrystals and nanostructured materials [4], crack nucleation and initiation of ductile fracture [3], pentagonal rods and icosahedral micro- and nanoparticles [1,3], amorphous solids and glasses [3], domains, and twins in ferroelastic films adjusted to a bulk substrate [5], and defects in graphene [6].

[1] A.E. Romanov and A.L. Kolesnikova, Application of disclination concept to solid structures, *Progress in Materials Science*, 2009, vol. 54, No 6, pp. 740-769.
[2] A.E. Romanov, A.L. Kolesnikova, Elasticity boundary-value problems for straight wedge disclinations. A review on methods and results, *Reviews on Advanced Materials and Technologies*, 2021, vol. 3, No 1, pp. 55-95.
[3] A.E. Romanov and V.I. Vladimirov, Disclinations in crystalline solids, in F.R.N.Nabarro ed. *Dislocations in solids*, North-Holland, Amsterdam, 1992, vol. 9, pp. 191-402.
[4] A.A. Nazarov, A.E. Romanov, and R.Z. Valiev, On the structure, stress fields and energy of nonequilibrium grain boundaries, *Acta Metallurgica et Materialia*, 1993, vol. 41, No 4, pp. 1033-1040.
[5] A.E.Romanov, M.J. Lefevre, J.S. Speck, W. Pompe, S.K. Streiffer, and C.M. Foster, Domain patterns in epitaxial rhombohedral ferroelectric films. II. Interfacial defects and energetics, *Journal of Applied Physics*, 1998, vol. 83, No 5, pp. 2754-2765.
[6] A.E. Romanov, M.A. Rozhkov, A.L. Kolesnikova, Disclinations in polycrystalline graphene and pseudo-graphenes. Review, *Letters on Materials*, 2018, Vol. 8, No 4, pp. 384-400.

MODEL COHESIVE PARTICLE ASSEMBLIES

Roux J.-N.
Universit'e Gustave Eiffel, Laboratoire Navier, Champs sur Marne, France
jean-noel.roux@univ-eiffel.fr

While cohesionless granular materials have been subjected to intense research efforts over the last decades, cohesive particulate assemblies are relatively seldom investigated.

However, they exhibit a wider variety of microstructures and mechanical behaviours, due, in particular, to the cohesion-induced stability of very open, tenuous contact networks akin to colloidal aggregates and gels. The planned lecture will focus on DEM simulations of simple models, with experimental confrontations whenever available. It will briefly review some recent results and outline perspectives regarding the following issues: characterization of microstructures of static assemblies under stress; quasistatic consolidation under growing stress intensity; critical states and dense flows with cohesion-enhanced shear resistance; quasistatic deformation under growing deviatoric stress. Important features to be mentioned and discussed include density correlations, the role of rolling and pivoting resistance in contacts, and the identification of characteristic pore sizes.

MOLECULAR DYNAMICS MODELING OF THE MECHANICAL BEHAVIOR OF YSZ-CERAMICS/GRAPHENE NANOCOMPOSITE

Rozhkov M.A.[1,2], Smirnov A.M.[2], Kolesnikova A.L.[1,2], Gutkin M.Yu.[1,2]
1 - Institute for Problems of Mechanical Engineering RAS, St. Petersburg, Russian Federation
2 - ITMO University, St. Petersburg, Russian Federation
marozhkov@itmo.ru

Functional nanoceramics are widely used in various industries, such as, for example, power engineering. In particular, new ceramic nanocomposite based on yttrium stabilized zirconia (YSZ) with the filler in the form of graphene layers is a promising material which has both ionic (oxygen) conductivity, inherent in YSZ ceramics, and electron conductivity due to the formation of clusters of graphene in the intergranular space [1, 2]. Such material can serve as a basis for creating an efficient molecular oxygen pump with possible applications in power engineering, engine building, fine chemical synthesis technologies and design of new medical equipment. At the same time, the desire to achieve better functional properties (such as strength, hardness, response to the concentration of oxygen in the gas phase over a wide range of temperatures through more intensive grain refinement or usage of new filler materials) often leads to degradation of mechanical properties of fabricated samples [3]. A purposeful search for ways to improve the functional properties of nanoceramics and ceramic nanocomposites, without sacrificing their mechanical characteristics, requires the development of theoretical models describing the mechanisms of strength and plasticity of such materials.

In the present work, we represent our first results on computer modeling of mechanical behavior of YSZ ceramics/graphene nanocomposites within the molecular dynamics approach. Our model was a YSZ crystal with a deformable graphene inclusion. The interaction between the graphene and the YSZ ceramics was described by various potentials of atomic interactions.

To solve the problem, it was necessary to select a potential that would adequately describe the mechanical behavior of the model under deformation. A detailed study of various interatomic potentials was carried out to refine the model and to obtain the results. In result we choose a combination of the Buckingham (B), ReaxFF and Lennard-Jones potentials (B-ReaxFF-LJ combination). The B-ReaxFF-LJ combination in solving the test problem made it possible to build a stable model and to obtain explainable results. The B-ReaxFF-LJ combination in solving the test problem made it possible to build a stable model and to obtain explainable results. In this case, the B potential was used to describe the

interaction between yttrium, zirconium, and oxygen atoms, the ReaxFF potential to describe the interaction between carbon atoms in graphene, and the LJ potential, using the Lorentz-Berthelot mixture rule, to describe the interaction between graphene and yttrium, oxygen and zirconium atoms. This combination of potentials was chosen for further modeling. Based on our results in modeling these objects with LAMMPS software package, we consider the dynamics of the structure evolution and the mechanical behavior of a separate graphene nanoinclusion and discuss the possibility to transfer these data to the behavior of real nanocomposites.
This work was supported by the Russian Science Foundation (RSF, project 18-19-00255, Mechanics of bulk functional nanoceramics and ceramic nanocomposites).

References
[1] Comins J.D., Ngoepe P.E., Catlow C.R.A., J. Chem. Soc. Faraday Trans. 86 (1990) 1183.
[2] Shackelford J.F., Doremus R.H., Ceramic and glass materials: structure, properties and processing, Springer, New York, U.S.A. (2008).
[3] Ovid'ko I.A., Philos. Trans. Roy. Soc. A 373 (2015) 20140129.

STUDY OF THE FORMATION OF SUPERDENSE MATTER ARISING FROM THE COLLISION OF GIANT MOLECULAR CLOUDS WITH THE HELP OF HETEROGENEOUS COMPUTING SYSTEMS

Rybakin B.
FSC SRISA RAS
rybakin@vip.niisi.ru

Most stars in galaxies exist as gravitationally bound binary and multiple systems. The process of formation of new star systems is the result of complex processes that occur in the interstellar gas. These processes include non-linear interactions of turbulence, gravity, MC rotation and a number of other factors. The evolution of the formation of superdense matter, starting from the moment when they are collected in turbulent flows, or are formed during supersonic collisions of molecular clouds (MO) with each other, until the moment when these superdense regions reach prestellar density. In addition, taking into account the rotation of molecular clouds has a great influence on the ongoing processes. The rotation of molecular clouds during collisions has been taken into account relatively recently [1].
Modeling of such astrophysical processes in a three-dimensional setting on ultra-high resolution grids requires very large computer capacities. The paper presents computer simulation of large-scale processes of formation of filaments and superdense, gravitationally bound structures (clumps) on parallel computing clusters with a hybrid architecture. Parallel simulation on supercomputers was carried out using the author's DarkMatter program, which uses a modified Godunov method of the second order of accuracy of the TVD type on 1024x1024x1024 grids. To refine the calculations, the AMR adaptive grid refinement method is used. The gravitational potential is calculated on GPUs.
The results of calculations are presented for variants of a frontal collision of two MCs, in which the density is distributed along the radius according to certain laws. The impact speed of each MO is 5.32 km/sec, rotation speed $\Omega=2.6\text{x}10^{-15}$, radius MC_1=13.44 parsec, MC_2=13.76 parsec. The cloud masses are 693 and 675 solar masses, respectively. The initial density contrast between the density in the MC center and in the interstellar medium is equal to $\chi=\rho_c l/\rho_{ism}=500$. The initial density of the interstellar medium is $\rho_{ism}=2.15\text{x}10^{-25}$ g/cm^3. The computational area has dimensions of 40x40x40 parsecs.
Numerical simulation of collisions of molecular clouds with and without rotation was performed with the optimization of parallel acceleration of the calculation on multi-core processors and graphics accelerators. Accounting for the rotation of molecular clouds introduces additional dissipative effects in the fragmentation of MC remnants. This leads to a spiral distribution of emerging lumps and the appearance of a corrugated structure with divergent fluctuations in the density of the substance in the core of the neoplasm. The simulation performed showed that the bunch density reaches values of the order of 10^{-20} - 10^{-19} g/cm3, which corresponds to the prestellar density, which, in the absence of additional influences, can lead to the onset of gravitational collapse [2].
Acknowledgements. This work supported by RFBR Grant 19-29-09070 mk.

Literature
1. Guang-Xing Li, F. Wyrowski, and K. Menten. Revealing a spiral-shaped molecular cloud in our galaxy: Cloud fragmentation under rotation and gravity. A&A, 598, A96, 1-15, (2017).
2. Rybakin B., Goryachev V.: Modeling of density stratification and filamentous structure formation in molecular clouds after shock wave collision. Computers and Fluids, 173, 189-194 (2018).

INTERNAL CONVECTION IN A LAYERED AIR-POROUS-AIR SYSTEM WITH HEAT SOURCE DEPENDENT ON SOLID FRACTION

Sagitov R.V., Kolchanova E.A.
Perm State University, Perm, Russia
sagitovrv@mail.ru

The onset of penetrative convection via internal heating in a three-layered system made up of a horizontal air layer partially filled with a heat-generating porous matrix under the gravitational field is investigated. The system consists of an air-saturated granular porous sublayer sandwiched between the two air sublayers free from porous matrix. The volumetric heat source is placed into the porous sublayer. Its strength is proportional to the solid volume fraction. The values of thermal conductivities and volumetric heat capacities are chosen to be typical for a biologically active porous medium with the solid elements containing water in their compositions. The three-layered system is bounded by solid impermeable planes with the same fixed temperatures. Two air sublayers have equal depths.
A three-domain model accounting for the Navier-Stokes equation in the two air sublayers and the Darcy equation in the porous sublayer is applied. The explicit expressions for temperature are found in each of the sublayers. Basic temperature grows with increasing the solid fraction and reaches its highest value at the middle of the porous sublayer.
The linear stability analysis has been carried out for the basic thermal profile with respect to the small normal disturbances periodic along the horizontal axis. It has revealed that different types of the convective rolls corresponding to distinct minima of the marginal stability curve can be most dangerous, depending on the values of control parameters. The rolls are either local short-wave flows which form mainly within the upper air sublayer or the large-scale long-wave convective flows which cover the upper air sublayer and a part of the porous sublayer where the basic state is unstably stratified. One has drawn the stability maps for the critical internal Darcy-Rayleigh number and wave number versus the solid fraction by varying the depth ratio and vice versa versus the depth ratio by varying the solid fraction. An abrupt LW-to-SW transition accompanied by a break of the marginal stability curve and a jump-like decrease in the critical wave number by times or tens of times are observed. The large-scale long-wave disturbances dominate at a relatively small solid fraction or depth of the air sublayer. One has obtained a regime map which includes a demarcation line between the large-scale and local convective regimes and a region of parameters for the bimodal marginal stability curves. The demarcation line demonstrates the solid fraction decreasing with the growth of the air sublayer depth. A destabilizing effect is for the solid fraction. It means that the critical Darcy-Rayleigh number decreases as this parameter increases. The air sublayer depth has also destabilizing effect on the stability threshold.
The work was supported by the Russian Science Foundation (Grant No. 21-71-10045), https://rscf.ru/en/project/21-71-10045/.

ABOUT THE POSSIBILITY OF EXPERIMENTAL CREEP CURVES USING TO DETERMINE THE METALLIC MATERIALS DAMAGE

Arutyunyan A.R., Saitova R.R.
Saint Petersburg State University, Saint Petersburg, Russia
rigastr@yandex.ru, a.arutyunyan@spbu.ru

The problem of high-temperature creep and long-term strength of metallic materials is demanded in such important fields of modern engineering, as thermal and nuclear power plants, aircraft and spacecraft, etc. Because these effects are observed in elements of many important engineering objects, the problem of brittle fractures became a subject of numerous theoretical and experimental research. The damage conception was introduced in the mechanics of materials to describe long-term strength under conditions of high-temperature creep. This conception has been developed in the fundamental works of Kachanov [1] and Rabotnov [2]. Rabotnov proposed a system of two interrelated kinetic equations for creep deformation and damage parameter.
Earlier we suggested a system of equations for damage parameter and creep deformation for compressible medium (Arutyunyan model [3, 4]), where the continuity parameter is given as relative density changes. In this work we propose to determine the continuity parameter changes according to the experimental high-temperature creep curves. Only one kinetic equation for creep rate for compressible medium, recorded using the continuity parameter, is formulated.
From this equation the continuity parameter is determined, depending on the creep rate and the creep deformation. Similarly, the value of the continuity parameter is determined according to the Rabotnov solution. To describe the experimental creep curves, various empirical dependences in the form of power, exponential and mixed functions are used. It is shown that for the case of a compressible medium a more intensive damage accumulation and, accordingly, damage processes are observed compared with the Rabotnov theory.

[1] Kachanov L.M. About fracture time under creep conditions // Izv. USSR Academy of Sciences. OTN. 1958. N 8. P. 26-31. (in Russian).
[2] Rabotnov Y.N. On the mechanism of long-term fracture // Questions of strength of materials and structures. M.: Izd-vo USSR Academy of Sciences. 1959. P. 5-7. (in Russian).
[3] Arutyunyan A., Arutyunyan R., Saitova R. The Criterion of High-Temperature Creep of Metals Based on Relative

Changes of Density // WSEAS Transactions on Applied and Theoretical Mechanics. 2019. 14. P. 140-144.
[4] Arutyunyan A.R., Arutyunyan R.A., Saitova R.R. Evolution of the processes of damage to the elastic-plastic medium in high-temperature creep // Proceedings of the Scientific and technical conference on the structural mechanics of the ship, dedicated to the memory of Professor V.A. Postnov and the 90th anniversary of his birth, St. Petersburg. 2017. P. 92-93.

THE INFLUENCE OF FOLDED RELIEF OF THE GUARD CELL SURFACE ON STOMATAL MOVEMENTS

Pautov A.A., Bauer S.M., Ivanova O.V., Krylova E.G., Sapach Yu.O.
St Petersburg University
a.pautov@spbu.ru

Stomata are structural elements of plant epidermis. They are composed of two guard cells divided by a stomatal pore. Stomata control transpiration and gas exchange. Their guard cells are capable of reversible deformation. As a result of this deformation, the stomatal pore opens or closes. The structural features of the guard cells responsible for their deformation are still under debate. It is believed that stomatal movements depend mainly on turgor pressure in the guard cells and on the structure of the guard cell walls, including their uneven thickness.
All guard cells have outer ledges formed by cuticle and located on their upper sides not far from the stomatal pore. The guard cells can also bear folds that surround stomatal ledges forming marginal stomatal rings. Typically, the rings result from the folding of the cuticle itself. The subcuticular space of such folds can be filled with pectin or with fibrous wall-like materials. To elucidate the role of the rings, we have applied dynamic modeling using the finite element method. The data on the shape of the guard cells, on uneven thickness of their walls, on localization and relative sizes of stomatal ledges and rings were accurately reproduced during model stoma construction. Turgor pressure was simulated by creating the load distributed over the inner surfaces of the guard cells. Stomata with marginal rings are located on the subsidiary cells. The dynamic modeling has shown that the marginal stomatal rings are able to influence the movements of the guard cells. The turgid guard cells without outer ledges and marginal stomatal rings bulge above the leaf surface. The wide opening pore between such guard cells moves in the same direction and rises above the leaf surface as well. The outer ledges prevent wide opening of the stomatal pore and cause its sinking below the leaf surface. Stomatal rings can enhance this effect. The influence of marginal rings on stomatal movements depends on the mechanical characteristics of the rings, namely on their rigidity and squeezing of stoma by them. The formation of rigid rings or rings squeezing the stoma in addition to rigid ledges leads to the deepest sinking of the open pore below the leaf surface.
The methods of light, scanning and transmission electron microscopy have shown that a stoma can bear not only one, but many folds which either form several stomatal rings, or intertwine with each other, forming massive compound stomatal rings. In some plant species, stomata are surrounded by peristomatal rims tightly pressed against the marginal stomatal rings. Unlike the stomatal rings, the peristomatal rims are located not on the stomata, but on the cells around them. It has also been established that stomatal rings can be induced by undulate morphology of the cellulose cell walls. Taking into account all these data allows to adjust simulation results and reveals a stronger influence of stomatal rings on the movements of the guard cells. Marginal stomatal rings have been found in plants that occupy different positions in the APG IV taxonomic system, in both archaic and evolutionarily advanced plant groups. This indirectly indicates the essential role of these structures.
The research was carried out with the support of the Russian Science Foundation grant No. 22-24-00572, https://rscf.ru/en/project/22-24-00572 /.

APPLIED PROBLEMS OF STATIC TRANSVERS BEND, STABILITY AND VIBRATIONS OF A GRAPHENE SHEET

Sargsyan S.H.
State University of Shirak, Gyumri, Armenia
s_sargsyan@yahoo.com

The construction of continuous models of deformations of two-dimensional nanomaterials, in particular that of graphene, is one of the topical problems in the mechanics of deformable solids. It is established [Panin, V. E. (1998). Fundamentals of physical mesomechanics. *Physical Mesomechanics* 1(1)] that the deformation of crystalline nanomaterials takes place based on the "shear plus rotation" deformation model. In [Ivanova, E.A., Krivtsov, A.M. & Morozov, N.F. (2007). Derivation of macroscopic relations of the elasticity of complex crystal lattices taking into account the moment interactions at the microlevel. *PMM*. 71(4); Berinsky, I.E. et al. (2014). *Modern problems of mechanics. Mechanical properties of covalent crystals*. In A.M. Krivtsova and O.S. Loboda (Eds.) Saint-Petersburg: Polytechnical University Press.] it is also established that for the study of deformations of two-dimensional nanomaterials according to the continuous theory, the use of the three-dimensional moment theory of elasticity with independent fields of displacements and rotations is appropriate.
The above-mentioned studies facilitate the development of the continuous theory of deformations of two-dimensional

nanomaterials as an adequate theory of plates and shells according to the moment theory of elasticity. In paper [Sargsyan S. H. 2022. Beam and continuous-moment models of deformation of two-dimensional nanomaterials. *Physical Mesomechanics*. 25 (2)], a continual one-dimensional beam model of a linear atomic chain is constructed, when the atomic interaction in its discrete model are of force non-central and moment character. With the application of the mentioned model, the paper further demonstrates the construction of the discrete-continuous model, replacing the interaction between the atoms of a two-dimensional nanomaterial with a beam system. On the example of a graphene, by passing to the limit, two continuous models of deformation are constructed: 1) a model of a plane stress state of a graphene sheet, 2) a model of its transverse bend, with the establishment that both of these models are identical to the corresponding models of the moment-membrane theory of elastic plates [Sargsyan S. H. 2020. A thin shell model within the moment theory of elasticity with the concept of deformation by shear plus rotation. *Physical Mesomechanics*. 23 (4)] and all the six elastic constants of the moment theory of elasticity for the graphene material are determined. Thus, we can state that the moment-membrane models of a plane stress state and the transverse bend of elastic plates, with already known elastic constants, can be interpreted as continuous models for the corresponding deformations of a graphene sheet.

It is clear that the mentioned continuous models open up new avenues for setting and studying various applied problems for graphene sheet deformations. In this paper, for the transverse bend of a graphene sheet, the following applied problems are studied: 1) the problem of static transverse bend of a rectangular graphene sheet, where we determine the bending of the graphene sheet; 2) the problem of stability for the initially compressed state of the graphene sheet, where we determine the critical load; 3) the problem of the free transverse bend vibrations of a graphene sheet, where we define the frequencies of natural vibrations and show that the minimum natural vibration frequency of a graphene sheet is in the terahertz frequency region.

EFFECT OF MATERIAL ANISOTROPY ON THE CRACK INTERACTION WITH FREE BOUNDARY AND OTHER CRACKS

Savikovskii A.V.[1], Semenov A.S.[1], Kachanov M.L.[2]
1 - Peter the Great Saint-Petersburg Polytechnic university, Saint-Petersburg, Russia
2 - Tufts University, Medford, Massachusetts, USA
savikovskii.artem@yandex.ru

Single crystal nickel based superalloys are widely used for gas turbine blades, which are the most loaded and critical components of gas turbine engines. Single crystal superalloys have the best characteristics of high temperature strength, resistance to thermal creep deformation, thermal fatigue durability and resistance to corrosion or oxidation. However, they have a pronounced anisotropy of mechanical properties, which leads to the complication of stress-strain state calculation and that's why crack resistance of anisotropic material needs detailed study.

The stress intensity factor (SIF) is the universal parameter for the crack characterization in the linear fracture mechanics. While the problem of SIF calculation for structures from isotropic materials is well-developed [2], the problem of SIF computation for anisotropic materials is more complex and less studied.

We consider the anisotropic rectangular plate under uniaxial tension with different number of edge cracks (one, two and three cracks). Plate sizes were varied and influence of interaction between crack and near and far boundaries on SIF values was analyzed. For the plate with three cracks the effect of distance between cracks on SIF values of the middle crack was analyzed and discussed. SIF were calculated by stress extrapolation method using Lekhnitskii formalism [3, 4]. SIF computations were carried out using the finite element software PANTOCRATOR [5]. SIF values for the isotropic material, the material with cubic symmetry and the orthotropic material were compared.

The results of computations have shown that SIF values change in different way for different classes of anisotropy, when free boundary is close to cracks. Simulations have shown that interaction between cracks is negligible for the distance between the cracks is more than 20 lengths of crack (in this case crack behavior can be described by single crack in infinite plane approximation). The result of insensitivity of cracks to each other is approximately the same for isotropic and different anisotropic materials.

[1] Getsov L. B. Materialy i prochnost detaley gazovykh turbin [Materials and strength of gas turbine parts], in 2 Vols. - Vol. 1. - Gas Turbine Technologies Publishing, Rybinsk, - 2010 (in Russian).
[2] Kachanov M., Shafiro B., Tsukrov I. Handbook of elasticity solutions. Boston: Springer, 2003. – 330 p.
[3] Lekhnitsky S.G., Teoriya uprugosti anizotropnogo tela [Theory of elasticity of an anisotropic elastic body], Nauka, Moscow, 1977 (in Russian).
[4] Semenov S.G., Semenov A.S., Getsov L.B, et al., Application of linear and nonlinear fracture mechanics criteria for crack propagation analysis in single crystal bodies, Proc. XLI Int. Summer School–Conf. "Advanced Problems in Mechanics (APM-2013)" St. Petersburg, Russia, July 2–6 (2013) 75–82.
[5] Semenov A.S. PANTOCRATOR – finite-element program specialized on the solution of non-linear problems of solid body mechanics. Proc. of the V-th Int. Conf. "Scientific and engineering problems of reliability and service life of structures and methods of their decision". SPb: Izd-vo SPbGPU, 2003. – p. 466-480.

FRACTURE MECHANISMS OF HYDROGEN-CHARGED METAL SAMPLES DURING A THREE-POINT BENDING TEST

Sedova Yu.S., Polyanskiy V.A.
Institute for Problems in Mechanical Engineering Russian Academy of Sciences (IPME RAS) Saint Petersburg, Russia
sedova.yus@mail.ru

Nowadays artificial hydrogen saturation of metal in an electrolyte solution or under cathodic charging is the main tool for testing materials for resistance to hydrogen embrittlement and hydrogen cracking. At the same time, it was experimentally established that this process always leads to a highly nonuniform distribution of the matter along the sample breadth. In this case, the concentration of hydrogen in a surface layer with a thickness of about one grain size can exceed its content inside the body by an order of magnitude. Despite of this the study of the nature of hydrogen embrittlement of the metals and alloys was performed without taking into account the influence of this skin-effect on the mechanical properties of the material.

In this work, we have carried out a numerical study of the influence of the skin effect of hydrogen saturation of samples on the crack growth in three-point bending. A single edge notched bend (SENB) specimen made of X70 pipe steel is considered. The Oriani brittle fracture model of hydrogen enhanced decohesion (HEDE) was chosen as the model for hydrogen embrittlement. The idea of the classical approach was developed by taking into account the possible elastic-plastic behavior of the body under the influence of acting stresses. We used our experimental data on the actual nonuniform hydrogen concentration in the sample and the available data on the hydrogen diffusion coefficients, diffusion activation energy, steel characteristics, cohesion law values, and other parameters of the HEDE model. The simulation was carried out on the basis of the finite volume method using the program code developed by us.

As a result of the calculations, the crack propagation parameters were obtained. It was established that the fracture pattern has a compound character. At the initial moment, destruction is initiated as brittle, induced by hydrogen. Later, it can proceed without the participation of a substance in accordance with the traditional approach of the theory of crack growth. It was shown that when the fracture propagates to a certain length, a local plastic deformations zone is formed at the crack tip, which, subsequently, can lead to the initiation of plastic fracture. The establishment of this fact explains the dual, brittle-plastic nature of fracture during mechanical loading of metal samples after their artificial saturation with hydrogen without involving complicated models of hydrogen destruction.

The research is carried out under the financial support by the Russian Foundation for Basic Research (project No. 20-08-01100).

HIGH STRAIN RATE BEHAVIOR OF CARBON/EPOXY COMPOSITES SUBJECTED TO ELECTRICAL EXPLOSION OF CONDUCTOR

Sergeichev I.V.[1], Fedorenko A.N.[1], Sudenkov Yu.V.[2]
1 - Skolkovo Institute of Science and Technology, Center for Materials Technologies, Moscow, Russia
2 - Research Center of Dynamics, Saint Petersburg State University, Russia
i.sergeichev@skoltech.ru

Strain-rate dependency of fiber-reinforced composites subjected to dynamic tensile loading is required for many structural applications involving exposure to intensive impact loads. Particularly, advantages of high specific strength are used in confinement composite vessels designed for transportation of sensitive explosives. For research, the windowless, portable, composite vessel allows lines of sight for X-ray or proton imaging. In the present study the previously developed laboratory setup was adopted for shock wave loading of cylindrical filament wound T700/L113 specimens by electrical explosion of thin copper conductor. To implement this technique, specimens were fabricated by winding of carbon fiber layers with directions 0° and ± 45° over Plexiglas rods with a diameter of 20 mm. The total thickness of the wound layers was 2 mm. The rods were cut into testing specimens of 30 mm long. Holes with a diameter of 1 mm were drilled along the axis of the cylinders to install the copper conductor with a diameter of 0.5 mm. The free surface speed of the specimens under explosion was measured by laser interferometer in radial direction and then circumferential tensile stress was calculated. It was assumed that the stress gradient is negligible inasmuch as the travel time of the shock wave through the thickness of the composite shell is several times less than the length of the loading pulse. As results, the failure stress was obtained for the discharge energies 0.9-1.9 kJ as 2200-3400 MPa for 0° layup and 1400-2200 MPa for ± 45° one. Taking into account the static longitudinal strength 1900 MPa, significant strain rate sensitivity of the unidirectional CFRP can be mentioned in the microsecond range of failure loading.

The research was supported by Russian Science Foundation https://rscf.ru/en/project/21-19-00563

ENERGY DYNAMICS IN THE A-FPU CHAIN AND CORRESPONDING CONTINUUM SYSTEMS

Shcherbinin S.A., Krivtsov A.M.
Peter the Great St.Petersburg Polytechnic University
stefanshcherbinin@gmail.com

Previously an analogy between mass transfer (in space) and energy transfer (in solids), as well as two new concepts of "carrier" and "phantom", was proposed. A carrier is a medium that enables energy transfer. A phantom is a virtual body of matter having its mass distribution equivalent to the energy distribution in the carrier. It is basic to the so-called energy dynamics approach. In the present paper applicability of this approach for particular nonlinear systems is examined. We consider the alpha-FPU chain and its two continuous versions, being described by the Boussinesq equation and the KdV equation. The connection between carrier-phantom description and classical results for the KdV solitons obtained with the aid of inverse-scattering transform are shown. For a nonlinear system of a general type, it is shown that time-averaged quantity describing the position of an energy phantom satisfies the same equations as for the Hooke chain. Numerical experiments confirming our analytical results are performed.

MECHANISMS OF STRENGTH OF METAL ALLOYS WITH GRAIN BOUNDARY SEGREGATIONS

Bobylev S.V.[1,2], Sheinerman A.G.[1,2], Enikeev N.A.[3], Valiev R.Z.[3]
1 - Institute for Problems in Mechanical Engineering
2 - Peter the Great Saint Petersburg Polytechnic University
3 - Ufa State Aviation Technical University
asheinerman@gmail.com

A model is proposed explaining enhanced strength of ultrafine-grained alloys that contain grain boundary (GB) solute segregations. In the framework of the proposed model these segregations are considered as homogeneous ellipsoidal inclusions and act as the sources of elastic stresses affecting the emission of lattice dislocations from GBs. These segregations pin the ends of lattice dislocation segments at the initial stage of dislocation propagation along GBs, and the unpinning requires a load increase, leading to the enhanced yield strength. In the case of the 1570 UFG Al alloy, the model predicted the increase in the yield strength due to GB solute segregations in the range from 100 to 300 MPa, depending on the segregation shape (aspect ratio) and number density. We demonstrate that the maximum yield strength of this alloy is achieved in the case of clustered, nearly spherical Mg segregations with a high Mg concentration and a diameter to thickness ratio of 1.0–1.4, depending on the Mg concentration inside segregations. This implies that strengthening requires the formation of GB solute segregations in the form of small concentrated clusters, instead of homogeneous distribution of solutes over GBs. The results of the calculations agree well with experimental data.

ANALYTICAL SOLUTUIONS FOR WATER INJECTION-INDUCED HYDRUALIC FRACTURING

Shel E.V.[1,2]
1 - Polytechnic University, Moscow, Russia
2 - Gazpromneft Science&Technology center
shel.ev@gazpromneft-ntc.ru

Hydraulic fractures, induced by the water-injection on the law permeable oil field, is a well known problem in the industry. Such a problems usually occurs without engineering intention, although these fractures can improve the general hydrocarbon recovery.
This report dedicated to the approximate analytical solutions for the water-injection induced fractures, including those, which was not derived in literature before.
According to these solutions, these fractures expected to have a rectangular form with the length larger than the fracture height. According to the parameters of the water-injection induced fractures, the fluid leak-offs and the fracturing toughness would be the dominant energy dissipation mechanism, comparing to the viscous dissipation. The average fracture width will be constant on fracture length, depending only on toughness of the reservoir rock and fracture height. Fracture penetration in the adjacent layers expected to be negligible. Fracture length depends only on the fluid leak-offs in the reservoir, fracture height, fluid injection rate and square root of the injection time.
Analytical solution for the fracture form is derived in the basis of the minimum of the potential energy, including the fracture surface energy and the energy of the elastic deformation.

COMPRESSIVE SOLITARY WAVE IN BLACK PHOSPHORENE

Shepelev I.A.[1], Kolesnikov I.D.[1], Dmitriev S.V.[2]
1 - Saratov State University, Saratov, Russia
2 - Institute of Molecule and Crystal Physics, Ufa Federal Research Center, Ufa, Russia
igor_sar@li.ru

Compressive solitons arise in crystals as a result of shock loading, and they can transfer energy over long distances, exhibiting weak damping. Propagation of compressive soliton waves in two-dimensional (2D) materials is studied much less than in 3D crystals. At the same time, 2D materials is one of the most perspective materials at nowadays. In the present work, molecular dynamics is used to analyze the behavior of compressive solitons in single-layer black phosphorene. We analyze general mechanisms of energy dissipation of the wave in the lattice. The results obtained are compared with those obtained earlier for graphene and boron nitride. The damping of compressive solitons in phosphorene is stronger than in graphene and boron nitride, since it has a puckered structure and, therefore, more channels for energy dissipation. We also show that the energy losses constantly attenuate in time due to a decrease in the frequency of phonon vibrations in the lattice. Overall, our results contribute to understanding the nonlinear dynamics of localized excitations in 2D materials.

COMPUTATIONAL ANALYSIS OF THE MECHANISMS OF QUASI-STATIC AND DYNAMIC FRACTURE OF SILICA REFRACTORY AT THE MESOSCALE

Shilko E.V.[1], Grigoriev A.S.[1], Dmitriev A.I.[1], Zabolotskiy A.V.[1,2], Andreev K.P.[3]
1 - Institute of Strength Physics and Materials Science of Siberian Branch Russian Academy of Sciences (ISPMS SB RAS), Tomsk, Russia
2 - Magnezit Group, Satka, Chelyabinsk region, Russia
3 - Wuhan University of Science and Technology, Wuhan, China
shilko@ispms.ru

Silica refractory is highly demanded in modern metallurgy as a material for heat-shielding elements of coke oven batteries, heat exchangers of blast furnaces, and glass-making furnaces. The features and microstructural aspects of crack formation and propagation in silica refractories under quasi-static and dynamic loading are attracting special research attention. Among the key factors influencing fracture behaviour, strength and energy absorption capacity are the pore structure and sintered interfaces between SiO2 grains.

To study the low-scale mechanisms of fracture of silica refractory, the mesoscale mechanical model has been developed and implemented within the method of homogeneously deformable discrete elements (DEM). We modeled silica refractory as a composite with a “soft” matrix (containing the microsized grains and micropores), “hard” mesoscale inclusions (grains of SiO_2), and mesoscale pores. The key problem in the development of the model was the determination of the local strength characteristics of the mesostructure components. An algorithm for solving this problem is proposed and validated. It is based on obtaining (1) primary experimental estimates based on data from macroscopic (compression, wedging) and local (indentation) tests, and (2) numerical dependences of elastic moduli as well as compressive and tensile strength on the type (morphology) and the value of porosity. The estimated mesoscopic parameters are then scaled to achieve the required values of macroscopic sample strength and geometric parameters of cracks being formed.

Results of computer simulation made it possible to reveal the patterns of change in the mechanisms of refractory fracture with an increase in the loading rate. In the region of quasi-static strain rates, the dominant contribution to fracture (up to 50%) is made by damage of the matrix (i.e., microscale structural elements). Upon transition to strain rates corresponding to dynamic loading, the most part of damage (up to 90%) is localized in large (mesoscale) SiO_2 grains and at interfaces with small (microscale) grains. We showed that the revealed change in the scale of structural elements that determine material damage occurs in the range of strain rates from 10^{-1} s^{-1} to 10^{0} s^{-1}. The results allow us to propose a physical criterion for determining the boundary of the quasi-static loading regime for quasi-brittle materials. The criterion is based on a comparative analysis of the contributions of structural elements to fracture.

The study was funded by the Russian Science Foundation grant No. 22-19-00688, https://rscf.ru/project/22-19-00688.

ON THE USE OF ELASTIC LIMITERS IN TWO-MASS VIBRATING MACHINES WITH SELF-SYNCHRONIZING INERTIAL VIBRATION EXCITERS

Panovko G.Y., Shokhin A.E.
Mechanical Engineering Research Institute of the Russian Academy of Sciences (IMASH RAN), Moscow, Russia
shohinsn@mail.ru

The work is devoted to the problem of ensuring the stable operation of technological vibrating machines with self-synchronizing inertial vibration exciters in near-resonance oscillation modes. The dynamics of vibromachines, designed according to a two-mass dynamic scheme, is considered when the working element oscillations are excited by two self-

synchronizing vibration exciters fixed on it. The influence of the parameters of the elastic limiter installed between the working element and the second movable body of the machine (which can also be considered as the second working element) on its oscillations and synchronization of the vibration exciters rotation in the resonant frequency ranges is analyzed. It is shown that the introduction of an elastic limiter into the vibromachine elastic system can lead to a significant expansion of the frequency range near the second resonant frequency, in which the synchronous antiphase rotation of vibration exciters required for the normal operation of the machine is realized. In addition, in this frequency range, the sensitivity of the oscillation amplitudes to changes in the material mass on the working element decreases, thereby ensuring the stability of the ongoing technological process. In this case, the magnitude of the oscillation amplitude can be regulated by adjusting the initial gap between the limiter and the vibromachine working element.
This research is funded by the Russian Science Foundation, project No. 21-19-00183, https://rscf.ru/en/project/21-19-00183/.

A VARIANT OF THE MECHANISM DESCRIPTION FOR THE DIELECTRIC HEATING

Shorkin V.S.[1], Vilchevskaya E.N.[2]
1 - Orel State University named after I.S. Turgenev, Orel, Russia
2 - Institute for Problems in Mechanical Engineering, Russian Academy of Sciences (IPME RAS), St.Petersburg, Russia
v.s.shorkin@yandex.ru

The mechanism and description of dielectric heating is proposed, that is, heating of a solid polar dielectric under irradiation with a high-frequency electric field. The description is made within the framework of the micropolar elastic materials model proposed by the authors. This model is based on the notion of non-local translational and orientation interactions between continuous medium macroparticles-dipoles, which is a polar dielectric model. Translational nonlocality is described by the Morse potential, and orientation nonlocality is described by the Stockmeier potential. The use of ideas about non-local interactions made it possible to calculate the material constants of a micropolar medium based on the physical properties of the material data.
A dielectric heating distinctive feature is of volume heat release in the heated medium. Electric harmonic monochromatic waves transfer their energy to the material, going deeper into it, gradually, in cycles. It is assumed that each cycle is not harmonic, but piecewise constant. The electrical energy transfer occurs at the beginning of the cycle instantly, changing the internal energy by a jump. Its change is zero in the remaining time. Therefore, the work of internal forces is equal to the thermal effect, which is expressed in terms of the temperature occurred change.
The micropolar medium model constructed by the authors indicates that in a nonstressed material, under the action of an alternating electric field, internal stresses arise at each cycle, which are not considered by the classical micropolar media theory. Their values are not equal to zero in the absence of external mechanical influences. Their work per cycle is also not zero. It is expressed in terms of the electric wave and the microparticles-dipoles characteristics that model the matter molecules. The work and the thermal effect equality establishes the relationship between the increase in temperature and the characteristics of an electric wave and of a material.
The resulting internal stresses generate acoustic waves in the material at each cycle. The micropolar environment model describes them. By simulating a set of these waves with a phonon gas, we can find another relationship between the electric wave and microparticles-dipoles characteristics with changes in the temperature of the material.
The theoretical reasoning is illustrated by an example of estimating the silicon wafer temperature change under the an electric field influence by a given frequency from a given power source.

HEAT AND MASS TRANSFER IN A PLANE HORIZONTAL LAYER OF FIBROUS POROUS MEDIUM WITH LOW THERMAL CONDUCTIVITY AND INTERNAL HEAT SOURCE

Sidorov A.S., Kolchanov N.V.
Perm State University, Perm, Russia
sidorovaliksandr@mail.ru

The work is devoted to an experimental study concerning a fibrous porous media with an internal heat source and low thermal conductivity. The characteristics of heat and mass transfer in a plane horizontal layer of the porous medium saturated with gas or liquid are investigated. Convection in such a medium is considered as an additional method of the removal of heat from the system [1-3].
We have manufactured porous media with given thermophysical characteristics in order to provide the possibility of controlling the heat source strength. To organize a uniform volumetric heat generation, the fibers of porous medium are made of a thin nichrome wire with a diameter of 0.09 mm. To increase the fiber size, one applies a Plexiglas coat to the wire with a thick up to 0.9 mm. The entire porous medium consists of the fibers woven into a photopolymer frame created by a 3D printer. The fibers are combined into an electrical circuit and connected to an electrical current source. When the electrical current passes through the fibers, they began to heat up the porous medium internally. To measure heat fluxes, we place a porous sample in a specially made working cavity with a volume of $100\times100\times13$ mm^3. The horizontal boundaries of the cavity are thermally conductive whereas the side walls are thermally insulated.
In the case of a heat-generating porous medium saturated with air, one has found the volumetric heat source strength

and effective thermal conductivity. For a porous medium saturated with water, the thermally conductive and convective regimes of heat transfer through one of the horizontal boundaries of the porous medium have been considered. The dependence of the Nusselt number on the temperature difference across the porous layer has been obtained and the permeabilities of porous samples have been calculated.
The work was supported by the Russian Science Foundation (Grant No. 21-71-10045), https://rscf.ru/en/project/21-71-10045/.

References
[1]. Alawee, Wissam, H., et al.: Numerical analysis of non-Darcian mixed convection flows in a ventilated enclosure filled with a fluid-saturated porous medium. Thermal Science and Engineering Progress 24, 100922 (2021) https://doi.org/10.1016/j.tsep.2021.100922
[2]. Mukhija, S., Nayak, A.K.: Experimental study of transient heat transfer characteristics of single-phase natural convection in multidimensional porous bed with volumetric heat generation // Experimental Heat Transfer. 32(1), 85-101 (2019) https://doi.org/10.1080/08916152.2018.1485782
[3]. Kolchanova, E., Kolchanov, N.: Onset of internal convection in superposed air-porous layer with heat source depending on solid volume fraction: influence of different modeling. Acta Mechanica. 233, 1769-1788 (2022) https://doi.org/10.1007/s00707-022-03204-8

NUMERICAL STUDY OF THE INFLUENCE OF VASCULAR BED CURVATURE IN THE AREA OF THE ABDOMINAL AORTIC BIFURCATION UNDER DIFFERENT CARDIAC OPERATING MODES

Sinitsyna D.E.
Peter the Great St. Petersburg Polytechnic University, St. Petersburg, Russia
sinicina.daria@yandex.ru

The methods of computational fluid dynamics used for a study of the pulsating flow in a rigid model of the average configuration of the abdominal aortic bifurcation and iliac arteries were conducted, in addition to maximum deviations of the characteristic angles of arteries branching. The temporal and spatial evolution of three-dimensional blood flow is studied depending on the curvature of the vascular bed, together with the heart rate (beats per minute - bpm) - variants of rest and exercise state of the heart are considered.
The 4 geometric model configurations used in the numerical simulations were built on the basis of clinical data from about 800 patients, and include a section of the vascular bed of three bifurcations: the abdominal aorta (AA) and the common iliac arteries (CIA). In the considered three-dimensional models, the characteristic branching angles of the arteries are the angle between the CIA and the lower section of AA (160°, 180°), together with the angle between the common and external iliac arteries (EIA) (90°, 120°), which varied within the physiological range.
The values and ratio of flow rates were selected based on clinical data obtained from the examination of 25 healthy patients. The period of the pulsation cycle is T = 0.86 s, 0.5 s, which corresponds to the state of rest (bpm = 70) and the exercise state of the heart (bpm = 120). The maximum Reynolds number at the inlet of the AA is $Re_{max} = 1875$ for bpm = 70, and $Re_{max} = 2782$ for bpm = 120, Womersley number $Wo \approx 13$ and 17, respectively.
In this work, the greatest interest is the cross-flow structure, which is formed at the outlets of the iliac arteries. In EIA, at the beginning of the cycle, a single-vortex flow is formed, which transforms into a two-vortex one (paired Dean vortices) in the phase of increasing flow, and remains almost until the end of the pulsation cycle. The right and left branches are almost completely identical in terms of the cross-flow structure. The listed features are typical for all model configurations, the existing differences are insignificant.
The characteristic vortex structure of the flow described above differs slightly from that with an increased bpm, while it should be noted that at the outlet of EIA, various patterns of cross-flow are predicted that are unstable during the cycle - a two-vortex or four-vortex structure.
In both internal iliac arteries (IIA), a stable pair of longitudinal Dean vortices is formed, which persists in all model configurations at rest and exercise state of the heart during the entire pulsation cycle, with the exception of the reverse phase of flow rate at bpm = 70, in which a stable single-vortex flow is formed.
According to clinical data, the combination of high the wall-shear stress index values OSI and low the cycle-averaged wall shear stress values TAWSS are hydrodynamic conditions for the development of vascular wall lesions. This study shows that in the models under consideration, the outer wall of the CIA and the posterior wall of the EIA are dangerous places. A slight decrease in the angle between the CIA and the lower section of AA (160°) leads to the fact that the area of the abdominal aortic bifurcation also falls into the risk zone for the development of atherosclerotic lesions on the walls.
This study was carried out with the financial support of RFBR within the framework of the research project №20-31-90071.

MODELING OF THREADING DISLOCATION DENSITY REDUCTION IN ALN/AL_2O_3 HETEROSTRUCTURE WITH TRANSITION REGION

Smirnov A.M.[1], Odnoblyudov M.A.[1,2], Bougrov V.E.[1], Romanov A.E.[1]
1 - ITMO University, Saint Petersburg, Russia
2 - Polytechnic University, Saint Petersburg, Russia
smirnov.mech@gmail.com

Sapphire (Al_2O_3) still remains the most usable substrate material for III-nitride heteroepitaxy. Due to significant differences in the parameters of crystal lattices and thermal expansion coefficients between film and substrate materials, in the III-nitride film grown on Al_2O_3 substrate arise large internal stresses, which can lead to the formation and evolution of various defects including threading dislocations (TDs). The presence of TDs in the film is unadvisable, since TDs strongly deteriorate carrier transport and optoelectronic properties of semiconductor heterostructures and devices based on them [1,2]. The use of transition layer (e.g. porous layer) for the subsequent growth of the film allows to reduce the level of thermoelastic stresses in the film occurring when the heterostructure is cooled after the growth process is completed [3,4]. On the other hand, the presence of pores in the film can directly affect the behavior of TDs. It was recently shown that the presence of triangular pores in AlN film grown on the Al_2O_3 substrate leads to a significant decrease in dislocation density in the film [5]. To describe critical parameters of the heterostructure (pore size, film porosity, film thickness, etc.) and find its optimal configuration, it is necessary to construct the relevant theoretical models. Thus, in present work we propose numerical model that describes thermoelastic stresses in AlN/Al_2O_3 heterostructure with a porous film, and a reaction-kinetic model that describes the evolution of the TD density in this heterostructure depending on the porosity of the film. It was shown that the larger the base of the triangular pore and the lower distance between neighboring pores, the lower the total TD density in the AlN film grown on a Al_2O_3 substrate.

This work was supported from the Russian Science Foundation under Project No. 19-19-00617.

References

[1] A. Baranov, E. Tournie, Semiconductor lasers: fundamentals and applications, Woodhead Publishing Limited, Cambridge, 2013.
[2] F.A. Marino, N. Faralli, T. Palacios, D.K. Ferry, S.M. Goodnick, M. Saraniti IEEE Trans. Electron Devices. 57 (2010) 353.
[3] I.N. Ivukin, D.M. Artem'ev, V.E. Bugrov, M.A. Odnoblyudov, A.E. Romanov Phys. Solid State. 54 (2012) 2421.
[4] D. Artemiev, V. Bougrov, M. Odnoblyudov, A. Romanov, Phys. Status Solidi. 10 (2013) 89.
[5] H. Hirayama, S. Fujikawa, J. Norimatsu, T. Takano, K. Tsubaki, N. Kamata Phys. Status Solidi. 6 (2009) S356.

SPACE FLIGHT SAFETY IN LOW EARTH ORBITS

Tyurenkova V.V.[1], Nikitin V.F.[1], Smirnov N.N.[1,2]
1 - Federal Science Center "Scientific Research Institute for System Analysis Russian Academy of Sciences"
2 - Moscow M.V.Lomonosov State University
mech.math.msu@inbox.ru

Effective mechanical shielding of Space vehicles is an acute problem since the flights in outer Space face the Space debris problem, especially at low Earth orbits and geosynchronous orbits. The main idea of protecting Space vehicles from hypervelocity small (character size of 1 cm order) fragments is to dissipate the impact energy in some way by the shielding layer. Simple increasing of the vehicle shell thickness is not effective as at speeds of the order of kilometers per second the depth of penetration is big and the total weight becomes unacceptable for a practical usage.

The new concept suggested in the beginning of the 21-st century states that protecting the spacecraft by a honeycomb of small gas-filled containments could form a much more efficient shield with lower mass. As multi-sheet shielding concept uses thin shield elements to repeatedly shock the impacting projectile to cause its melting and vaporization, so is the new gas-filled containment shield concept still using continuous effect of pressurized gas to cause fragments slowing down, heating, melting, atomization and evaporation. Besides, using many successive layers of gas-filled spherical bumpers makes it possible to increase the area of the zone of impact energy redistribution including the side and front walls of bumpers due to the property of gas to transmit pressure in all directions, which provides a considerable advantage to the present concept as compared with multi-layer shields.

The gas-filled bumper shields could be reusable, as the rate of gaseous phase leakage effect on depressurization is rather low and the loss of mass is negligible during the characteristic time of impact.

SINUSOIDAL THERMAL EXCITATION: KINETIC AND DYNAMICAL APPROACHES, EFFECT OF DIMENSIONALITY AND DISPERSION

Sokolov A.A., Borisenkov B., Krivtsov A.M.
Peter the Great St.Petersburg Polytechnic University, St.Petersburg, Russia
sokolovalexey1@gmail.com

Anomalous thermal conductivity is a thermal conduction regime that differs from the classical Fourier law. It is observed at the micro and nanoscale and in low-dimensional materials. Recently, studies of anomalous thermal conductivity have attracted increased interest due to advances in nanotechnology. Of particular interest is the purely ballistic regime leading to thermal superconductivity.

Transient Thermal Grating is very effective for the experimental study of this phenomenon. In this experiment, an ultrafast sinusoidal thermal excitation is created on the sample surface. Then the change in amplitude over time is measured, which describes the characteristic features of the process.

This work is devoted to a theoretical description of this experiment. The problem of initial thermal sinusoidal excitation for the purely ballistic case is addressed by two approaches: by the method of lattice dynamics and by the kinetic theory of phonons. A medium with and without dispersion is considered, as well as a medium of different dimensionalities d = 1, 2, 3.

The change of amplitude over time is obtained for each case. The influence of the presence of dispersion and the medium's dimensionality on the process's characteristic features are obtained.

STUDY OF THE EFFECT OF BRIDGING ON THE DYNAMICS OF AUTO HYDRAULIC FRACTURE GROWTH

Sokolova D.A., Kalinin S.A.
Peter the Great St. Petersburg Polytechnic University, Russia
daryya.sokolova@gmail.com

Increasing injection pressure on injection wells often leads to unplanned fractures (these fractures are called auto-fracturing). The occurrence of these fractures is highly undesirable, as it can have irreversible consequences up to the watering of the oil reservoir, which significantly worsens the quality and quantity of recoverable oil. At best, the formation of an autograder fracture leads to a decrease in injection pressure in the injection well and significantly complicates the formation pressure maintenance process. Therefore, the task of modeling the propagation of auto-pipe fracture in order to control it is urgent.

An important parameter influencing the dynamics of autograined fracture growth is colmatation – the process of natural penetration of small particles contained in the injected water into pores and fractures of rocks. Colmatation significantly affects rock permeability and, consequently, pressure distribution in the reservoir, which, in turn, affects the dynamics of fracture growth.

The purpose of this work is to solve the problem of the effect of colmatation, which in this work is considered in terms of geomechanics as a problem of fluid filtration in a porous medium with particle deposition.

BEM BASED APPROACH FOR NUMERICAL SIMULATION OF SINGLE-PHASE AND MULTIPHASE FLOW IN MICROMODELS OF POROUS MEDIA

Solnyshkina O.A., Fatkullina N.B., Bulatova A.Z.
Center for Micro- and nanoscale dynamics of dyspersed systems, BSU, Ufa, Russia
olgasolnyshkina@gmail.com

The detailed investigation of hydrodynamic flows in the porous medium at the microscale, taking into account the structural features of the pore channels, is crucial to predict the behavior of reservoir fluids in porous media and their study at the macro level. One of the generally accepted ideologies of representation of porous media is the capillary model, when the volume of porous medium is considered as a network of microchannels of complex shapes. Since pore channels have natural irregularities of different scales, inevitably arising features on their surfaces and deviation of the shape from the idealized cylindrical or plane-parallel considered in most works should be taken into account and thoroughly investigated both experimentally and numerically. Furthermore, additional porosity scales can be introduced to describe some processes more accurately. Such approaches are used to describe processes in a fractured-porous reservoir.

This work is dedicated to the development and application of the computational approach to study the features of hydrodynamics flow and dynamics of deformable dispersed inclusions in a flow in different configurations of micromodels of porous media. Numerical approach is based on the accelerated Boundary Element Method (BEM). Application of the conventional BEM for solving the problems of dispersed flow in microchannels of complex shape is frequently limited by the computational and memory complexity. To resolve these difficulties, the BEM was accelerated both due to a highly efficient scalable algorithm (Fast Multipole Method) and due to the use of heterogeneous

computing architectures (multi-core CPUs and graphics processors). We developed efficient codes, which enable direct three-dimensional simulation of Stokes flow in microstructures of complex structure with tens of thousands of discrete elements on the surface. The possibility of using the approach for calculating flows in microchannels with irregularities of various shapes, as well as in micromodels with wide porosity scales, is demonstrated. The influence of the structural parameters of micromodels on the distribution of flow between regions with different porosities was studied. The comparison of the simulation results of the flow pattern with the data obtained in the experiment on microfluidic devices manufactured using the "lab-on-a-chip" technology was carried out and showed the qualitatively agreement. Furthermore, we study the influence of irregularities of various sizes and shapes on the microchannels walls on hydrodynamic characteristics of the viscous fluid flow and the deformable droplet dynamics in viscous fluid flow. The proposed approach and the obtained results can be used in research of practically significant problems associated with the single and multiphase flows in media with different porosity scales.
The reported study was funded by the Russian Science Foundation within the research project No.217910212.

HIGH-ORDER HOMOGENIZATION APPROACH FOR EVALUATION OF THE LENGTH SCALE PARAMETERS OF STRAIN GRADIENT ELASTICITY

Solyaev Y.O.
Institute of Applied Mechanics RAS
yos@iam.ras.ru

High-order homogenization approaches assume that the overall macroscopic behavior of the equivalent medium can be described based on generalized continuum theories. In the present study we consider the problem of determination of the effective material constants for the composites with ellipsoidal inhomogeneities assuming that the equivalent media corresponds to the strain gradient elasticity theory (SGET). SGET allows to provide a refined analysis for the processes with high level of stress concentration, e.g. for the problems with cracks [1], concentrated forces [2], or high-frequency vibrations [3].
Analytical method for determination of the effective elastic moduli and length scale parameters of SGET is developed based on high-order homogenization approach with non-uniform boundary conditions and extended Eshelby equivalent inclusion method [4]. Explicit solutions are derived for the composites with ellipsoidal orthotropic inhomogeneities within the dilute, the self-consistent and the differential schemes. Examples of calculations are presented for the composites with isotropic phases and spherical inclusions, which provides a micromechanical validation for the constitutive equations of simplified strain gradient theories.

[1] Vasiliev, V., Lurie, S., Solyaev, Y. (2021). New approach to failure of pre-cracked brittle materials based on regularized solutions of strain gradient elasticity. Engineering Fracture Mechanics, 258, 108080.
[2] Solyaev, Y., Lurie, S., Altenbach, H., dell'Isola, F. (2022). On the elastic wedge problem within simplified and incomplete strain gradient elasticity theories. International Journal of Solids and Structures, 111433.
[3] Metrikine, A. V., Askes, H. (2002). One-dimensional dynamically consistent gradient elasticity models derived from a discrete microstructure: Part 1: Generic formulation. European Journal of Mechanics-A/Solids, 21(4), 555-572.
[4] Solyaev, Y. (2022). Self-consistent assessments for the effective properties of two-phase composites within strain gradient elasticity. Mechanics of Materials, 169, 104321.

COMPUTER SIMULATION OF SOLID FUEL COMBUSTION IN HYBRID ENGINE

Nikitin V.F., Stamov L.I., Mikhalchenko E.V., Tyurenkova V.V.
SRISA RAS
lyubens@mail.ru

In this work a three-dimensional computational simulation of the processes occurring in the combustion chamber of a hybrid solid fuel engine was done. A hybrid engine is a system that use fuel and oxidizer in different aggregation states. Such hybrid systems are attractive because of their advantages over classic solid fuel or liquid rocket engines. In this work HTPB (Hydroxyl-Terminated PolyButadiene) and PMMA (PolyMethylMethAcrylate) were considered as a solid fuels. Gaseous oxygen and air were considered as oxidizing agents. Mathematical model for simulation of gas-dynamic processes based on RANS (Reynolds-averaged Navier–Stokes) equations was used. Explicit second-order in space and time method based on the MUSCL-interpolation (Monotonic Upstream-centered Scheme for Conservation Laws) of variables on a face at a convective flux calculation and the AUSMP (Advection Upstream Splitting Method Plus) method for compression terms was used. Accounting for chemical interactions was done by solving the stiff system of chemical kinetics differential equations by using the fourth-order semi-implicit Novikov method from the Rosenbrock family of methods with double calculation of the right-hand side of the system and one-time calculation of the Jacobian. The turbulence was modelled using the k-ω Wilcox turbulence model. OpenMP technology was used for parallel execution support. Verification and validation of a numerical scheme was done by using an analytical solution and experiment data for HTPB and PMMA fuels. Comparison of computer simulation results with experiments data showed satisfactory agreement. Distributions of the main parameters in the model combustion chamber were obtained. Large

turbulization of the flow, formation of vortices, a strong nonsymmetry of the process and unsteady nature of the occurring processes were observed. Influence of turbulence and instability decreases when solid fuel burns out.
Russian Foundation for basic research is acknowledged for financial support (RFBR 20-07-00587).

MATHEMATICAL MODEL OF THE KINETICS OF THE CHEMICAL REACTION OF POLYMERIZATION OF A BIFUNCTIONAL EPOXY RESIN (ED-20) AND A SIX-FUNCTIONAL TRIETHYLENETETRAAMINE (TETA) UNDER VACUUM CONDITIONS, TAKING INTO ACCOUNT THE EVAPORATION OF COMPONENTS WITH A LOW MOLECULAR WEIGHT

Komar L.A.[1], Kondyurin A.V.[2], Svistkov A.L.[1,3], Terpugov V.N.[3]
1 - Institute of Continuous Media Mechanics of the Ural Branch of Russian Academy of Science, Perm, Russia
2 - Ewingar Scientific, Ewingar, Australia
3 - Perm State University, Perm, Russia
terpugov@psu.ru

Polymeric materials based on epoxy resins, due to the uniqueness of their properties, are widely used in the space industry. They have the necessary strength and low weight. This makes it possible to use these materials to create sufficiently large space objects, for example, antennas with a reflecting part radius of several tens of meters. Currently, the greatest interest of aerospace developers is in the creation of inflatable structures, the bearing elements of which are made of prepregs. The opening of such structures should be carried out in space by maintaining the internal air pressure, which cannot be constant. Further maintenance of the shape of the structure is carried out by curing the load-bearing elements from the prepreg. The advantage of such structures over metal ones is that they are lighter and more densely packed into the container of the spacecraft, which will deliver the structure into orbit around the Earth. It should be emphasized that during the curing process, all structural elements are exposed to high vacuum and sudden temperature changes from -150 to 150 degrees Celsius, that is, under conditions significantly different from those on earth. In particular, for this reason, it is topical to study the phenomenon of evaporation of low molecular weight molecules of the reaction mixture.
The developed mathematical model is intended to describe a specific chemical curing reaction of prepregs impregnated with ED-20 epoxy resin and TETA hardener. The model is a system of ten first-order differential equations. The model can be applied to problems in two independent formulations, namely, both with and without evaporation. The problem in the statement without taking into account evaporation makes it possible to obtain a complete picture of the molecular weight distribution in time of all reaction groups, both amine and epoxy. The curing time in this case is determined by the equimolar ratio of the reacting epoxy and amine groups and the values of the chemical reaction rate coefficients, which significantly depend on the external temperature. When solving the problem taking into account evaporation, it was assumed that there is a thin boundary film with special properties at the boundary of the cured epoxy material, through which some of the molecules with low molecular weight, which are included in both the reacting and the initial epoxy and amine groups, escape into open space. The evaporation process is determined by taking into account diffusion phenomena during the redistribution of molecular masses. The additional boundary condition imposed in this case is derived from the assumption that evaporation occurs when the value of the kinetic energy of the molecule exceeds the value of the work expended by this molecule to overcome the energy barrier.
The reported study was supported by the Government of Perm Krai, research project No C-26/1025.

INVESTIGATION OF THE BRANCHING FLUID FLOW IN A BLOOD VESSEL MODEL WITH ULTRASOUND HIGH-FRAME RATE VECTOR FLOW IMAGING TECHNIQUE

Tikhomolova L.G., Yukhnev A.D.
Peter the Great St. Petersburg Polytechnic University, St. Petersburg, Russia
ludmila060495@mail.ru

One of the methods to restore blood flow in the lower extremities is bypass surgery. After a few years, in most cases, overgrowth of the vascular prosthesis occurs due to intimal hyperplasia - cells overgrowth on the inner surface of prostheses artery junction, as a reaction to mechanical damage during surgery. Studies point to blood flow disturbances as a factor that stimulates this process.
The work is aimed at obtaining experimental data on the flow structure in the model of the prosthesis branched from the femoral artery at different output flow rate ratios with a new ultrasound high-frame rate vector flow imaging technique (V-flow).
Recently a group of vector imaging techniques has been added to the traditional doppler ultrasound techniques for blood flow analysis. The advantage of the method is independence from the angle of inclination of the sensor relative to the direction of blood flow, as well as high frame rate (up to 500 Hz), with the ability to view the resulting video file at a rate of 1/7 to 1/200 of the actual one for detailed flow analysis.
3D model of the prostheses artery junction was built based on several personalized models obtained by MSCT angiography. The maximum input Reynolds number is 1000. Output flow ratios ranged from 30% to 70% of the input flow rate. Two-dimensional vector velocity fields and axial velocity profiles were obtained with the V-flow technique

implemented on the Mindray Resona 7 ultrasound scanner. According to the obtained fields, velocity profiles were built at the inlet and in the prosthesis at four instances of the cycle time.
It was found that vortex recirculation zone is localized at the prosthesis outer wall of the prosthesis. The size of the recirculation zone increases during the direct flow phase. There is no recirculation zone during the reverse flow phase. As the prosthesis ratio blood flow increases, the recirculation zone decreases. Its maximum dimensions are detected at the case of 30% of the inlet flow rate. The obtained experimental data on the flow in the model of the prosthesis branched from the femoral artery make it possible to determine zones where the risk of intimal hyperplasia is high.
The work was carried out with the support of the Russian Science Foundation, grant No. 20-65-47018, as well as technical support and assistance from Mindray Medical Rus LTD and Sonar-Medical LTD.

PRINCIPAL STRESS-STRAIN STATES OF THIN-WALLED COMPLEXLY BENT PIPELINES

Tkachenko O.P.
Computing Center of the Far Eastern Branch of the Russian Academy of Sciences
olegt1964@gmail.com

A mathematical model of a curved pipeline considered as an elastic shell loaded with an internal fluid flow with a pressure drop is investigated. Geometric restrictions on the permissible displacements of the pipeline are established, under which the proposed model can be applied. Equations for the dynamics of a pipe as a shell are derived from three-dimensional partial differential equations describing its stress-strain state. An asymptotic analysis of these equations is performed. Based on the obtained asymptotics, approximate problems are set that approximate the solutions of the equations of the mathematical model with different accuracy. Test examples are formulated, on the basis of which it is possible to separate the areas of application of various approximations of the mathematical model. The numerical solutions of test problems obtained in various approximations are compared with their known exact solutions. A correspondence between the values of the parameters of the mathematical model and the most appropriate statement of the approximate problem is established. This correspondence can be used to select the optimal method for analyzing the stress-strain state in terms of its efficiency and sufficient accuracy. The original numerical solutions of test examples are compared with the solutions of the three-dimensional problem obtained by the finite element method in the FreeCAD design environment. It has been established that the solutions obtained by the proposed method deviate from the FEM solution by a small amount. Algorithms for performing computational experiments based on the proposed mathematical model have been created. The work has been supported by the Russian Science Foundation grant № 21-11-00039, https://rscf.ru/en/project/21-11-00039/.

INFLUENCE OF FLUID FILTRATION ON THE PROCESS OF FORMATION OF A FRACTURE

Torres T.M., Belyakov G., Tairova A., Iudochkin N.
Moscow Institute of Physis and Tecnology, Moscow, Russia
tauan@phystech.edu

The stress-strain state changes when a liquid is injected into the skeleton under high pressure, as a result, a fracture can form. The paper considers the conditions for the formation of a crack in a poroelastic medium during fluid filtration through it by the method of laboratory modeling.
The experiment showed that the elastic wave compressing the porous material moves along the flow direction. If the medium is not saturated with liquid, the elastic wave is running ahead of the filtration front. In case of porous media with static obstacles, in addition to compressive stresses, tensile stresses also arise. This occurs as a result of the fact that during compression, the permeable skeleton is shifted relative to its initial position and obstacle position. The movement of a porous medium is similar to the movement of a viscous fluid when flowing around an impermeable body. The main condition for the formation of a crack in a poroelastic medium is the excess of the tangential stresses of a viscous fluid on the porous material knowing the Young's modulus of this medium.
The research was carried out within the state assignment of Ministry of Science and Higher Education of the Russian Federation (theme No 122032900167-1).

ESTIMATION OF THE INFLUENCE LOAD HISTORY ON THE PORTEVIN-LE CHATELIER EFFECT IN AL-MG ALLOY

Tretyakova T.V., Wildemann V.E., Tretyakov M.P.
Perm National Research Polytechnic University, Perm, Russia
cem.tretyakova@gmail.com

The Portevin-Le Chatelier effect (PLC) is observed during inelastic deformation of Al-Mg alloys at a specific loading regime, including temperature and strain rate. The plastic flow localizes into narrow strain bands on the deformed materials. The spatial inhomogeneity leads to a significant decrease of plasticity and strength, reduce material surface quality. Spatial inhomogeneity and the spontaneous macroscopic localization causes a non-uniform thickness, and, as

consequence, to failure.
The aim of the present work is to estimate the influence of the load history on the Portevin-Le Chatelier effect in aluminium-magnesium alloy under complex loading in tensile tests with torsion. Thin-walled tubular specimens of an Al-6.12% Mg (wt. %) alloy were deformed in tension, tension after torsion and tension after tension-torsion with a two-axis servo-hydraulic testing system (Instron 8850) at room temperature. The digital image correlation technique was used to characterize the spatial-time inhomogeneity due to the Portevin-Le Chatelier effect. The processes of the PLC bands initiation and propagation are studied under complicated loading. The results show the close relationship between the load history, type of serrations on the stress-strain curves and the effect of quasi-periodic homogenization of plastic flow.

DYNAMIC ANALYSIS OF A NON-PROPORTIONALLY DAMPED STRUCTURES USING A HIGH-PRECISION FREE-INTERFACE COMPONENT-MODE SYNTHESIS METHOD

Tseytlin B.V.
"Vedeneev VNIIG", JSC, St.-Petersburg, Russia
tseitlinbv@vniig.ru

Vibrations of a precast reinforced concrete foundation for a turbine unit with a capacity of 1000 MW are considered. The foundation design includes vibration isolating elements and viscous friction dampers and is a system with disproportionate damping. The finite element method is used to form a mathematical model of the structure. Three methods were used to calculate oscillations under the action of operational vibration loads. The first is the dynamic stiffness method. Occurred errors are associated with the errors of finite element discretization only. The second and third methods are variants of the free-interface component mode synthesis method that takes into account the residual compliance matrix. When using these methods, the structure is divided into substructures. Within each of the substructures, the displacements are approximated by segments of series of real eigenmodes with a free boundary and residual terms that take into account the contribution of discarded high-frequency modes. Residual compliance matrices are used to account for these residual terms. Taking into account the conditions for the compatibility of interface displacements and the dynamic equilibrium of boundary nodes allows one to determinate the equations of oscillations with respect to unknown expansion coefficients. When using the second method, a frequency-independent real matrix is used as the residual compliance matrix. When using the third method, it is assumed that the residual compliance matrix is complex, and its real and imaginary parts depend on the frequency. Comparison of the results obtained using the above three methods made it possible to estimate the limits of applicability of the methods based on the use of the residual compliance matrix. In particular, taking into account the dependences of the real and imaginary parts of the residual compliance matrix on frequency makes it possible to determine a solution that fits accurately with the exact one.

EFFECTS OF SURFACE MICROGEOMETRY ON SOFT ELASTIC CONTACTS

Tsukanov I.Yu.
Ishlinsky Institute for Problems in Mechanics RAS
ivan.yu.tsukanov@gmail.com

Microgeometry of surfaces influences on the conditions of their contact and frictional interactions from which the functional properties of joints are depend and can be controlled. When one or both contacting surfaces are made of soft elastic materials the gap between them can be quite small even at low applied pressures. Considering intimate contact of surfaces, the shape and arrangement of asperities, as well as texture spatial orientation, will drastically affect the main contact characteristics of the contacting bodies - the real contact area, the maximum pressure and the interface gap. Also, due to the presence of several scales of surface asperities their interplay can lead to the formation of clusters of individual contact zones.
In this work mechanical effects associated with the behavior of contact characteristics during the interaction of multiscale regular microgeometry under the conditions of a small gap between the contact surfaces are considered based on the solution of elastic contact problems.
As a result, the following main conclusions for the contact of surfaces with regular microgeometry were suggested:
- the form of contact pressure distribution for single scale microrelief is generally defined by the shape of asperities;
- the increase in asperities density leads to an increase in the peak pressure, and also to the reduction of the real contact area at a fixed load;
- despite significant discrepancy in pressure distributions, elastic interaction of asperities produces considerable effect on the maximum pressure only for the high applied loads;
- for 3D sinusoidal wavy surfaces the mean contact characteristics at light and high loads mainly depend on geometry of axisymmetric component of Fourier series, representing three-dimensional sinusoidal surface;
- the continuous contact configuration is one of the two possible configurations, arising at indentation of a multiscale wavy surface into an elastic half-plane. This configuration leads to continuous oscillatory contact pressure distribution;
- the influence of the higher harmonics on the maximum pressure is significantly larger than on the mean pressure for

the same contact zone length;
- with an increase in the waviness amplitude, at which, with an increase in the load, a transition from a simply connected contact region to a multiply connected one occurs, the oscillation amplitude of "contact area-load" dependence increases, and the curve has a jagged shape. There is a transition mode in which a simply connected contact area alternates with a multiply connected one;
- contact geometry at initial touch (one or several contact zones) affects the size of the real contact area for multiscale regular asperities.

This research was funded by the Russian Foundation for Basic Research, grant 20-01-00400.

MODELLING OF WATER HUFF AND PUFF TECHNOLOGY IN A LOW PERMEABILITY OILFIELD

Tsykunov O.I.
Peter the Great St. Petersburg Polytechnic University, Russia
tsykunov.oi@gazpromneft-ntc.ru

This paper presents a study of the applicability of the water Huff and Puff technology using a dual porosity hydrodynamic model. The exploration of oilfields with hard-to-recover reserves is becoming an actual problem. The main category of such fields is tight reservoirs. The main difficulty in its exploration is low efficiency of the reservoir pressure maintenance system due to very low permeability (less than 1 mD), which leads to a low oil recovery factor and low well flow rates. The solution to this problem can be the water Huff and Puff technology. It consists of several cycles of three operations: injection water into the production well, stopping and production.

The physical principle of this technology is to initiate spontaneous capillary imbibition during water injection. If the reservoir is hydrophilic water under the influence of the capillary pressure will soak into small pores and displace oil into large pores. This process is described by the Laplace equation, which links the contact angle, surface tension, and capillary radius. The smaller the radius is, the higher the pressure is and, consequently, the technology can be more effective in tight reservoirs.

A synthetic hydrodynamic model was created in the tNavigator software to analyze the efficiency. The capillary imbibition process was calculated using a dual porosity and permeability model.

Since there is a system of large pores with active filtration and a system of small pores, in which there is no filtration, it can be compared with the matrix-crack system, where the crack is large pores, the matrix is a system of small pores. It is impossible to specify an additional pressure gradient between the matrix and the fracture, caused by capillary forces, in hydrodynamic simulator and the only way is to convert this gradient into the permeability change.

This logic was embedded in the script using the ARITHMETHIC keyword - at each calculation step the condition of the water saturation at which the imbibition starts is checked and then if there is an excess the permeability of the matrix is multiplied by the calculated coefficient depending on capillary pressure, formation pressure in the cell, initial permeability. The capillary pressure values were taken from the extrapolated capillary pressure curve from laboratory experiments.

To test the model, pilot work was carried out on 4 wells in the oilfield with low permeability. Due to the technological issues injection and shutdown regimes were not observed at three wells and there were problems with reservoir pressure. This is the reason to consider these tests substandard. In one well the optimal time was 30 days of injection and 30 days of shutdown for soaking. The only problem was the unstable well performance before the operation - the oil flow rate was very different from 0.5 to 5 t/day.

The results obtained for the pilot works are coherent with the model. The average oil production rate before the operation is 2 m^3/day, after the operation the maximum oil production rate is 5.5 m^3/day, in the model, respectively, 1.8 m^3/day and 5.48 m^3/day. At the same time, the dynamic of the oil production decline after the operation in the model matches with the decline during the pilot operation.

All in all, a simulation model of capillary imbibition was created for the Huff and Puff technology and the results of pilot works on the real well agree well with the created model.

ONE-DIMENSIONAL MAGNETIC CONTACTLESS SUSPENSION MODEL

Udalov P.P., Popov I.A., Lukin A.V., Skubov D.Yu.
Peter the Great St. Petersburg Polytechnic University
pp_udalov@mail.ru

This paper proposes a model of a micromachine accelerometer based on a contactless magnetic suspension. Analytical expressions for the period average equilibrium position of the levitating mass when the coil is powered by an alternating current of high frequency are obtained. Due to the non-analytic nature of the mutual inductance of two circular circuits, the method of multiple scales is applied to estimate the dynamics of the system near the equilibrium position. It is shown that the magnetic stiffness is a non-permanent quantity in the considered scenario of electromagnetic field excitation. The condition for non-negativity of the average period stiffness of the system is obtained. The issues related to increasing the sensitivity of the suspension are discussed.

EXPERIMENTAL INVESTIGATION OF A MODEL EMULSION DELAMINATION IN THE CELL HEATED FROM ABOVE

Valiullina V.I., Ayupov A.R., Musin A.A., Kovaleva L.A.
Bashkir State University, Ufa, Russia
vilenches@gmail.com

The issue of demulsification in the industry is no less significant than the issue of obtaining an emulsion. Demulsification is the basis of many technological processes: the production of butter and cream from milk, latex rubbers, dewatering of crude oil, wastewater treatment, as well as other processes. An increase in the temperature of the emulsion increases the speed of Brownian motion of droplets of the dispersed phase, and properly increases the probability of mutual collisions of droplets and their enlargement, reduces the viscosity of the "water in oil" emulsion and the density difference of the dispersed phase and the dispersion medium, significantly reducing the first and slightly increasing the latter. It also helps to weaken the strength of the adsorption shells of emulsifiers on the surface of the droplets, and, in addition, to increase the solubility and peptization of the substance of the adsorption shells in oil, which contributes to an increase in the effectiveness of collisions of water droplets.
A study was carried out aimed at studying the effect of inhomogeneous heating from above on the stratification of the emulsion in this work. The experimental setup included a cell [1], two thermostats for heating and cooling the emulsion system, the experimental area of the cell was fixed on a camera. The illumination of the cell was carried out using a Sumita SM250 light source.
It was found that the degree of heating of the emulsion significantly affects the deposition time of water droplets as a result of experiments. It has also been found that with increasing temperature, the rate of separation of the emulsion increases. This is explained by the nonlinear exponentially decreasing dependence of the viscosity of the dispersion medium on temperature.

The reported study was funded by the grant of the Russian Science Foundation (project №19-11- 00298).
References:
1. Valiullina V. I. et al. Experimental study of the stratification of polydisperse emulsions in a cell with heated walls //Journal of Physics: Conference Series. – IOP Publishing, 2021. – T. 2057. – №. 1. – C. 012041.

HYBRID NUMERICAL SCHEME FOR THE SIMULATION OF GUIDED WAVE EXCITATION BY A PIEZOELECTRIC TRANSDUCER IN AN ELASTIC SUBSTRATE

Vareldzhan M.V., Eremin A.A.
Kuban State University, Institute for Mathematics Mechanics and Informatics, Krasnodar, Russia
michael.vareldzhan.777@mail.ru

Simulation and analysis of guided wave excitation by piezoelectric transducers in layered elastic solids are among the basic problems in ultrasonic-based non-destructive testing and active structural health monitoring. They demand on adequate and cost-efficient computational models that reliably describe the effect of such a load on an elastic substrate. When guided wave phenomena are evaluated with semi-analytical integral approach, all information about the source of vibrations enters integral and asymptotic representations for excited wavefields via the vector function of contact stresses. Therefore, if they are known in advance, it becomes possible to use all benefits of the integral approach for further parametric analysis, such as, e.g., fast computation of excited wavefields or possibility for investigation of energy distribution between particular normal modes.
Inspired by the work E. Moulin, et. al., JASA, 2000, 107(1) and the integral equation and asymptotics based approach developed by E.V. Glushkov and N.V. Glushkova, a two-stage hybrid scheme is implemented in the current research for the simulation of guided wave excitation by surface mounted piezoelectric transducer in a plane strain case. At the first stage, using the finite element method (FEM) enriched with perfectly matched layer (PML) formalism to simulate an open, infinite waveguide time-harmonic contact stresses between the transducer and the elastic substrate are calculated. They are further extracted from the obtained FEM solution and substituted into semi-analytical representations for wavefields. Despite the apparent simplicity, practical implementation of this approach has revealed certain computational issues leading to some disagreements between the results of the FEM model and the two-stage scheme. Therefore, an alternative approach is proposed, in which the components of the displacement vector are extracted from the FEM model rather than stresses, and the corresponding stress vector is found from the solution of the Wiener-Hopf integral equation in the contact area using the Galerkin method. Moreover, further modification of the scheme is implemented intending to avoid the typical problem of PML to handle frequency ranges where normal modes with negative group velocities exist. In this case transient broadband displacements from FEM model serve as an input being preliminarily converted to frequency domain via FFT.
In the current talk, peculiarities of the practical implementation of developed approaches are discussed, and their performance is illustrated for the case of an aluminium plate excited by piezoceramic wafer active sensors (PWAS) adhesively attached to its surface. Along with the corresponding parametric analysis regarding the influence of the PWAS geometry and adhesive properties on the excited guide waves the results of experimental verification are also

presented.

The work is supported by the state assignment of the Ministry of Science and Higher Education of the Russian Federation (Project No FZEN-2020-0017).

MULTICHANNEL DIFFUSION IN THE MCNABB AND FOSTER MODEL

Varshavchik E.A., Polyanskiy V.A.
Institute for Problems in Mechanical Engineering of the Russian Academy of Sciences, St. Petersburg, Russia
baziro2345@gmail.com

The diffusion of hydrogen in a solid is a complex process. There are many analytical and numerical models describing this process. However, each model has its drawbacks, because of which it does not accurately describe the experimental data. The purpose of this article is to combine two models of hydrogen diffusion: the McNabb and Foster model with the Fisher model. The McNabb and Foster model assumes the presence of hydrogen traps in the material that have certain binding energies and affect the diffusion process. Fischer's model considers multichannel diffusion without the influence of hydrogen traps. Multichannel diffusion allows us to consider the diffusion of hydrogen through various channels, each of which corresponds to a certain binding energy. Each of the models individually has its advantages, but some experimental data cannot be explained. By combining these models, it becomes possible to describe experimental data with great accuracy.

Cylindrical samples made of aluminum alloy D16 with a diameter of 4 to 8 mm and a height of 15 mm were considered in the experiment. These samples were placed in a heated extraction chamber of the experimental setup, where hydrogen desorption curves were determined using the mass spectrometry method. Then, the obtained experimental desorption curves were compared with the curves obtained by the combined model. Based on the comparison, conclusions were drawn about the advantages and disadvantages of the combined model.

The research is carried out under the financial support by Russian Science Foundation, grant 18-19-00160.

MATHEMATICAL SIMULATION OF MYOPIA CORRECTION USING MYORING IMPLANTATION

Bauer S.M.[1], Venatovskaya L.A.[1], Avershina L.A.[2], Terentyeva A.E.[2]
1 - Saint Petersburg State University, Saint Petersburg, Russia
2 - Cheboksary branch of S.N. Fyodorov National Medical Research Center “MNTK “Eye Microsurgery”, Cheboksary, Russia
l.venatovskaya@spbu.ru

The search for an effective method of correcting refractive errors remains one of the urgent tasks of modern ophthalmology. It is known that laser surgery lead to a significant weakening of the strength and biomechanical properties of the cornea, and in the case of thin corneas surgery is not performed. In present paper the mathematical model that describes the stress-strain state of the cornea after MyoRing implantation is presented. Initially, this technology was used to correct keratoconus, but recent studies show its effectiveness in the case of high myopia and thin corneas. Two-dimensional axisymmetric modeling is performed in the engineering simulation software ANSYS. The corneoscleral shell of the eye is modeled by joint spherical segments of variable thickness with different radii and different elastic properties. It is assumed that the ring is implanted in a corneal pocket with a diameter of 9 mm to a depth of 80% of the original thickness of the cornea. Large deformations of the joint shells under the action of intraocular pressure are considered. The influence of the diameter and thickness of the MyoRing implant on the stress-strain state of the eye and results of myopia correction are analyzed.

NON-REFLECTING BOUNDARIES FOR SEISMIC ANALYSIS IN THE SOIL-STRUCTURE SYSTEM

Vitokhin E.Yu.
Vedeneev VNIIG, JSC, St. Petersburg, Russia
vitokhineyu@vniig.ru

The choice of boundary conditions considering non-reflection for seismic analyses of systems “structure-foundation” is crucial. Dashpots sets are well-known and widely used in numerically modelling to provide that condition [1]. However, damping of vibrations associated with canyon sides swaying are not considered. Thus, springs are additionally used to eliminate that drawback [2, 3]. This work represents the method of determining these springs stiffness. The boundary where sets of springs and dampers are applied is named as double asymptotic. The seismic analyses of the system "Sayano-Shushenskaya dam – foundation" was carried out in Simulia Abaqus, considering the double asymptotic boundary, as well as viscous boundary implemented through infinite elements.

1. Lysmer J, Kuhlemeyer R. L. Finite dynamic model for infinite media // Journal of the Engineering Mechanics Division, ASCE, V. 95, N. 4, pp. 849-877. 1969.
2. Le-Zakharov S. A., Zeitlin B.V. Boundary Conditions at the Border of the Foundation Area when Calculating Vibrations of Hydraulic Structures. Proceeding of the VNIIG. 2020. Vol. 295. P. 78-89.

3. Tseitlin B.V., Vitokhin E.Yu., Le-Zakharov S.A., Fyodorov I.V. theoretical research of fluctuations of the concrete hydroengineering structures at seismic loads // Proceeding of the VNIIG. 2014. Vol. 271, P. 120-137.

CONSTITUTIVE MODELING OF 3D-PRINTED THERMO-INDUCED SHAPE MEMORY POLYMERS

Volgin O., Kolomenskiy D.
Skolkovo Institute of Science and Technology
oleg.volgin@skoltech.ru

Shape memory polymer (SMP) is a type of material that can recover its original shape from its temporary shape in response to external stimulus. Such programmable materials are often called "smart" due to their capability to actively change geometric configuration and have a large potential for medical and aerospace applications. Current research focuses on constitutive modelling of 3D-printed shape memory polymeric objects. The SMP in this study was a special thermoplastic polyurethane (TPU) filament, which is appropriate for fused deposition modelling (FDM) 3D-printing method. Manufactured objects demonstrate large recoverable deformations to the initial state being heated above glass-transition temperature Tg. In order to capture the SM effect of the thermally activated polymers, multi-branch constitutive models are often applied by considering the thermomechanical phase transition as the temperature crosses Tg. The model requires two distinct sets of non-equilibrium branches representing the glassy mode of relaxation and the Rouse modes in the rubbery state. This type of model is time- and temperature-dependent and applicable for 4D-printing with the fourth dimension referring to time. Various experiments were carried out to fully characterize the complex thermomechanical behavior of SMP: uniaxial tension and compression, thermal expansion, relaxation, constrained and free recovery mechanical tests. Overall, the model is able to capture the wide range of experimental results. In this work, a three-dimensional finite-element implementation of the constitutive model is presented. The obtained results of numerical calculations are in good agreement with experimental data; they reveal thermomechanical behavior of SMPs and provide accurate predictions for shape recovery process with respect to strains and stresses.

FRACTURE AND PHASE TRANSFORMATIONS IN CONTINUUMS UNDER DYNAMIC ACTIONS

Volkov G.[1,2], Petrov Yu.[1,2]
1 - Saint Petersburg State University, St. Petersburg, Russia
2 - Institute for Problems in Mechanical Engineering of the Russian Academy of Sciences, St. Petersburg, Russia
g.volkov@spbu.ru, y.v.petrov@spbu.ru

An influence of the dynamic actions to a phase state of the continuum is studied. A standard phase diagram describes the equilibrium state of a material and it is not evident whether some impact load leads to the phase transformation or not. The critical amplitude stress value of the impact causing the transformation usually differs from the value taken from the conventional phase diagram, which in most cases is interpreted as a local anomalous distortion of the phase diagram. On the other hand, in terms of transformation, it would be rather questionable to assume that an effect of the short stress pulse must be the same as one caused by a long action with equal stress amplitude. Meanwhile, the lack of good approaches to estimate the influence of dynamic loads on the phase equilibrium conditions results in the assumption mentioned above being implicitly applied in numerous studies.
In the paper, phase transitions in solids and condensed matter under dynamic loading are considered within a framework of a unified approach based on the incubation time concept. The way to estimate the dynamic action and its influence on phase transformation is given that predicts the possible distortion of the classic equilibrium phase diagram. The model allows explaining the mentioned anomalous effects as quite predictable ones in accordance with the structural-temporal approach. For instance, it is shown how an acoustic wave can change liquid-to-vapor equilibrium in water or how intensive impact pulses shift the melting conditions of aluminum. A similar approach allows us to predict also the structural transitions in fracture dynamics, where the competitive change of the material critical parameters can affect the origination of other essential processes such as brittle to ductile transitions.

THE IMPLEMENTATION OF THE ARTIFICIAL DEFECTS IN THE EXPERIMENTAL STUDY OF VERY HIGH CYCLE FATIGUE BEHAVIOUR OF ADDITIVELY MANUFACTURED 316L STAINLESS STEEL

Voloskov B.[1], Mishurova T.[2], Evlashin S.[1], Akhatov I.[1], Bruno G.[2,3], Sergeichev I.[1]
1 - Center for Materials Technologies, Skolkovo Institute of Science and Technology (Skoltech), Moscow, Russia
2 - Bundesanstalt für Materialforschung und –prüfung (BAM), Berlin, Germany
3 - Institute of Physics and Astronomy, University of Potsdam, Germany
boris.voloskov@skoltech.ru

Additive manufacturing (AM) allows design freedom compared to conventional manufacturing technologies. Despite the fact that the use of AM technologies in the industry is growing every year, there is still a lack of knowledge and experimental data of the very high cycle fatigue (VHCF) behavior of this type of materials. However, many structural components such as turbine blades or railway parts are often subjected to such complex loading as VHCF. Therefore, the study of VHCF is essential for the operation of AM materials in many industries. In the VHCF regime, the crack usually originates from internal defects, in contrast to high cycle fatigue (HCF), where the crack typically initiates at the outer surface of the specimen. The role of the initiation stage is particularly important for VHCF regime that is characterized by the generation of the specific zone on the fracture surface - fine granular area (FGA). Typically, the FGA surrounds the internal defect where the damage starts. At the present work, the artificial defects have been embedded into 316L stainless steel specimens produced by laser powder bed fusion to study the mechanism of the damage initiation in the VHCF regime. The cylindrical defects with diameter and depth of 90×250, 180×400, and 350×550 µm were embedded at several positions along the specimens' radiuses. After the VHCF tests of the specimens, it was observed that the defects did not initiate the FGA and crack formation when the defects were located in the vicinity of the specimen's centre. However, the crack initiated from the natural defects (voids etc.) located closer to the outer surfaces of the specimens. This effect could be explained by the presence of significant residual compressive stress distributed in the sample.

NUMERICAL SIMULATION OF THE PERMEABILITY OF UNIDIRECTIONAL CARBON FIBER REINFORCED COMPOSITE MATERIALS

Vorobyev R.I.[1], Moskalev I.V.[2], Akhatov I.S.[1], Sergeichev I.V.[1]
1 - Skolkovo Institute of Science and Technology, Moscow, Russia
2 - OOO "TESIS", Moscow, Russia
ruslan.vorobyev@skoltech.ru

Predicting the permeability of polymer composite materials (PCM) is important in experimental practice and production. Validated numerical methods for determining PCM permeability allow prediction of flow irregularities and other potential defects during fabrication. Carbon fiber PCMs have a much smaller effective fiber diameter as well as lower X-ray absorption than the widely studied glass fiber PCMs, which ultimately makes the process of analyzing carbon fiber materials to study structural properties extremely difficult. In this work, samples were extracted for CT imaging and segmentation of a separate set of 2D sections transverse to the fiber direction using PCM based on Toray T700 and epoxy resin. After the reconstruction of the model, the numerical simulation of the permeability along and across the fibers was performed using the combined finite volume method. The components of the permeability tensor were calculated by solving the corresponding boundary value problems within the three-dimensional Darcy law. As a result, a method for efficient estimation of the PCM permeability tensor components was proposed.

CALCULATION OF CURVATURE VARIATION ON HEATING OF A TWO-LAYERED PLATE WITH SHAPE MEMORY ALLOY AND ELASTOPLASTIC MATERIAL LAYERS AFTER PRELIMINARY BENDING OR TENSION

Volkov A.E.[1], Volkova N.A.[2], Vukolov E.A.[1]
1 - St Petersburg University, St. Petersburg, Russia
2 - St. Petersburg State Technological Institute (Technical University), St. Petersburg, Russia
e.a.vukolov@yandex.ru

Two-layered plate loaded by a tensile force and a bending moment is considered. The top layer is a functional one and consists of nickel-titanium (Ti 50% Ni 50%) shape memory alloy (SMA). The bottom layer is elastoplastic (steel). Constitutive relations of SMA are set by a microstructural model allowing calculation the strain increment (infinitesimal strain theory is used) caused by arbitrary stress and temperature increments. Relations of this model intended for calculating increments of the strain tensor and internal variables of the model are formulated basing on experimental data of the kinetics of martensitic transformation and taking into account the crystallographic features of the transformation and equilibrium thermodynamics. The evolution of the stress and of the martensite fraction distributions over the thickness of the plate is calculated stepwise by solving the boundary value problem for given small increments of the tensile force (or relative elongation) and the bending moment (or curvature). Euler–Bernoulli hypotheses are applied. The temperature is assumed uniform over the thickness of the plate. Two cases of preliminary deformations are considered: deformation caused by applying a bending moment (A) and deformation caused by stretching with the deflection constraint (B). After the preliminary deformation and unloading the plate rests in the bent shape and demonstrates the shape memory effect and the two-way shape memory effect on consequent heating and cooling across the temperature range of phase transformations. Simulation of this effect shows that the considered bimetal plate can serve as an active temperature-driven element of technical devices. The largest stroke can be achieved by choosing optimal thicknesses of the layers and by preliminary deformation in the mode of bending.

WAVELET METHODS FOR SOLVING NONLINEAR MECHANICAL PROBLEMS

Wang Jizeng[1,2]
1 - Key Laboratory of Mechanics on Disaster and Environment in Western China, the Ministry of Education, China
2 - College of Civil Engineering and Mechanics, Lanzhou University, Lanzhou, Gansu, China
jzwang@lzu.edu.cn

With the in-depth development of mechanical research to interdisciplinary and cross-scale correlation, the strong nonlinearity caused by extreme environment, intrinsic instability, and the coupling and correlation of different factors and different scales has become a significant mathematical feature of this new type of mechanical problems, which inevitably poses a severe challenge to related quantitative modelling and solution research. In view of this situation, based on the multi-resolution analysis theory of function space decomposition, using the mathematical framework of wavelet analysis, and starting from the construction of the underlying basis function, we put forward a highly efficient and high-precision approximation theory for numerical approximation of general functions, their derivatives and integrals, and developed a new system of numerical methods for solving the general nonlinear initial and boundary value problems in mechanics. The proposed solution methods have been extensively and successfully verified in the solution of strongly nonlinear mechanics problems with different characteristics.

DETERMINATION OF VISCOELASTIC PROPERTIES OF MODIFIED POLYURETHANE AT VARIOUS TEMPERATURES

Yakovenko A.A.
Ishlinsky Institute for Problems in Mechanics RAS
anastasiya.yakovenko@phystech.edu

Polyurethane is a material whose mechanical properties vary depending on the technology of its production. One of the field of application of this material is the development of biocompatible implants. This process is accompanied by the need to investigate the stress state of the implants in their use. This is usually done by FEM with the help of standard software packages. However, for correct calculation it is necessary to know the mechanical properties of the material. For this purpose, in this study, a number of experiments were carried out, the results of which made it possible to determine the viscoelastic properties of polyurethane at different temperatures.
There are various methods for determining the mechanical properties of materials, including rheological ones. In this study, the method of indentation was used since it has several advantages over other methods, including the simplicity of the experiment procedure, few requirements for the size and geometric parameters of the sample and the non-destructive nature of the test. The indentation process was carried out by a spherical ball with a constant loading speed. Since the contact area increased throughout the process, the Hertz solution and the method of replacing elastic constants with corresponding viscoelastic operators [1] were used to construct the contact model. The standard viscoelastic solid model (Boltzmann model [2]) was chosen to describe the mechanical behavior of the material.
The tests were carried out at three loading speeds and three temperature values. The results obtained at the lowest speed were used to determine the long-term elastic modulus. Then the results obtained at the highest loading speed were processed that allows us to find two other parameters of the model (creep and relaxation time). Finally, the obtained parameters were used to construct theoretical curves at the third value of the speed in order to compare them with experimental results. Thus, this approach made it possible to determine with a sufficient degree of accuracy the mechanical and rheological properties of polyurethane at different temperatures.
The reported study was funded by the Russian Science Foundation, project number 18-19-00574.
[1] Lee E.H., Radok J.R.M. The contact problem for viscoelastic bodies // Journal of Applied Mechanics. V. 27, No 3. 1960. Pp. 438-444.
[2] Chen D.-L., Yang P.-F., Lai Y.-S. A review of three-dimensional viscoelastic models with an application to viscoelasticity characterization using nanoindentation // Microelectronics Reliability. V. 52, No 3. 2012. Pp. 541-558.

EXPLOSION PHENOMENA DUE TO RAPID PHASE TRANSITIONS

Yakush S.E.
Ishlinsky Institute for Problems in Mechanics of the Russian Academy of Sciences, Moscow, Russia
yakush@ipmnet.ru

Rapid phase transitions with significant increase in the specific volume can cause explosive phenomena, referred to as “physical explosions”, in contrast to conventional explosions driven by the energy released in chemical reactions (combustion, detonation). For the physical explosions, the internal energy of the substances involved is converted into the mechanical energy of blast waves. This explosion type possesses various features rendering it an interesting scientific problem in the area of multiphase flows, gas dynamics, thermal physics etc. Two physical explosion types are considered in the paper: i) boiling liquid expanding vapor explosions occurring upon the burst of a high-pressure vessel filled with liquefied gas, and ii) steam explosions occurring when a high-temperature melt interacts with volatile liquid (water). Energy transformation paths are illustrated for each explosion type, and physical mechanisms limiting the energy release rate are highlighted. The development of pressure waves in the course of rapid boil-up of liquid is demonstrated by numerical computations. For the expansion of a volume of superheated liquid, a homogeneous equilibrium model of the two-phase flow is applied, in the formulation suitable for full and partially filled vessels. The calculated blast waves featured by multiple wave fronts agree quite well with experimental observations. For steam explosions caused by high-temperature melt interaction with water, the main stages of a steam explosion in various configurations and the mechanisms of the formation of the premixing region necessary for the implementation of the explosive interaction are analyzed. The results of experiments and three-dimensional numerical simulation of the interaction of the melt with water during the impact of a water jet on the surface of the melt and the penetration of the melt jet into water are presented. A single droplet steam explosion occurring under the action of an initiating pressure pulse is demonstrated, including the collapse of a vapor film, direct contact of water with the melt, oscillations of the vapor bubble, and fragmentation of melt. The analogy of steam explosion waves with detonation waves in chemically reacting systems is discussed.

CASCADE MODEL FOR THE HYDRAULIC FRACTURING PREDICTION BASED ON MACHINE LEARNING METHODS

Yurkin A.A.[1,2], Kondratenko F.I.[3], Murachev A.S.[3]
1 - PJSC Slavneft-Megionneftegaz, Megion, Russia
2 - Tomsk Polytechnic University, Tomsk, Russia
3 - Peter the Great St. Petersburg Polytechnic University, St. Petersburg, Russia
yurkin0660@mail.ru

Currently, the most common method of oil production stimulation is hydraulic fracturing. Usually it is necessary to make hydrodynamic models, in order to estimate the effect of this operation. Each model requires the involvement of highly qualified personnel and a significant investment of time to optimize the hydraulic fracturing design. As a result, the disadvantages of the classical approach to hydraulic fracturing calculation are increased operating costs at the preparatory stage and the impossibility of potential assessment for the entire well stock with high accuracy in a several days, even with all historical data gained. At the same time, the modern development of the oil industry implies an increase in the speed of operations and the degree of digitalization, which should reduce operating costs at the preparatory stage. In this article, the authors propose an automated method for assessing the effect of hydraulic fracturing based on historical data using machine learning (ML) methods.
To train ML methods and develop a mathematical algorithm, unloading from several databases was used. The columns in the dataset were divided into five groups according to their meaning: well operation parameters at the time of well shutdown, actual start-up parameters, predictive model parameters, hydraulic fracturing design data, information about the reservoir and its fluids. The number of hydraulic fracturing cases in the dataset is 5077.
After the data analysis, dependences were also obtained, that describe certain external factors: for example, the hydraulic fracturing performer (contractor) was the key parameter for predicting the start-up liquid water containing. Based on the results, it can be concluded, that the chemical compositions used by contractors have a significant impact on the starting value of the well water cut. The most accurate prediction results were obtained for the positive scenario. The results of predictions for the negative and the most realistic application scenarios differ within 5-10%.
The developed model makes it possible to obtain results that, on average, exceed the results of the analytical forecast. Thus, in the course of the work, a cascade model was obtained, which makes it possible to calculate the start-up parameters of the well after hydraulic fracturing with an accuracy comparable to analytical models. The key effect of using the resulting development is the reduction of time, since the inference of an already trained ML model is performed in an extremely short time (up to 5 seconds, depending on the data). It is also worth noting the lower average absolute error, which will allow us to build a more accurate forecast for all candidates in total.

ADAPTIVE CONTROL OF MULTIPLE SYNCHRONIZATION OF TWO-ROTOR VIBRATORY MACHINE WITH TRACKING OF GIVEN PHASE SHIFT BETWEEN ROTORS

Andrievsky B.R., Zaitceva I.S.
IPME RAS, St.Petersburg, Russia
juliazaytsev@gmail.com

Vibrating machines are widely used in various areas of production. Traditionally, the required modes of machine operation are ensured by the proper construction design and essentially used the phenomenon of self-synchronization of rotating unbalanced rotors. Recently the direction associated with the automatic control of vibration installations and related digitalization, feedback control, and intelligent and adaptive control methods has been developed. The development and implementation of these methods in vibration technologies can lead to more flexible, efficient, and economical vibration technologies. Within the framework of this approach, an adaptive control algorithm with an implicit reference model is proposed to ensure the operation of a two-rotor vibration machine in the multiple synchronization modes with a given phase shift between rotors tracking. The paper presents the results of intensive computer simulation of the proposed control algorithm for various values of the multiplicity of the rotor's rotational frequencies and a given phase shift between them. The experiment results conducted on the twin-rotor vibratory unit SV-2M based in the Institute of Mechanical Engineering of the Russian Academy of Sciences are presented. The figures illustrate the rotational speeds and phase shifts between the rotors. Also, the process of adaptive controller adjustment is shown. The performance of the vibration machine demonstrates the effectiveness of the proposed algorithm in wide operating modes. Further on, the development of automated control algorithms in vibration machines promises the transition toward intelligent vibration technologies. It allows regulating the type of vibration fields of the table in real-time, including improving the process of vibration mixing by chaotizing its movement.

ACTION OF PULSED CURRENT ON A CRACK-TYPE DEFECT AT THE CONDUCTOR EDGE

Alekseev D.I., Zhukov D.V., Krivosheev S.I., Magazinov S.G.
Peter the Great St.Petersburg Polytechnic University
s_zhukov51@bk.ru

The influence of pulsed current on the behavior of a crack-type defect at the edge of a conductor has been studied. As a result of a local increase in the current density at the tip of the defect, a pulsed magnetic field with an induction amplitude of 25-40 T or more is generated.
The conductor material in this zone encounters a multifactorial effect, which is mainly determined by the nonlinear diffusion of the magnetic field, heating and melting of the conductor, magnetic pressure, etc.
The analysis of experimental data and the results of numerical simulation in the Comsol MPh environment revealed two main factors determining the development of the defect due to an increase in the local current density at the tip of the defect.
The first factor is determined by the excess of the integral of the current action of the critical value for the material of the conductor. The second factor is thermal stresses, which are formed as a result of heating and melting of the conductor material, which arise due to the high local current density.
In this case, the stresses at the top of the defect can exceed the material tensile strength and form conditions for its destruction in the form of a discontinuity (crack)
The combination of acting factors at certain parameters of the pulse current leads to the formation of a specific shape of craters at the top of the defect. With repeated exposure to pulsed current, a catostrophic growth of the defect is observed, and its structure has a fractal character. According to the results of the studies, the parameters of the current pulse necessary to initiate the growth of the defect were determined.

TANGENTIAL SHORT-WAVE DIFFRACTION BY A JUMP OF CURVATURE: ALEXEY POPOV'S CASE

Zlobina E.A.[1], Kiselev A.P.[1,2,3]
1 - St. Petersburg State University, St. Petersburg, Russia
2 - Institute for Problems in Mechanical Engineering of the Russian Academy of Sciences, St. Petersburg, Russia
3 - St. Petersburg Department of Steklov Mathematical Institute of Russian Academy of Sciences, St. Petersburg, Russia
ezlobina2@yandex.ru

We aim at a construction of short-wave approximation for a wavefield governed by the scalar 2D Helmholtz equation. The wavefield satisfies the Neumann condition on the boundary C composed of the half-line $C_{-} = \{x < 0, y = 0\}$ and a piece of smooth contour $C_{+} = \{x > 0, y = y(x) < 0\}$. The parts C_{-} and C_{+} conjugate at the point $O = (0,0)$, and there the curvature of C undergoes a jump. The incident wavefield is a plane wave $\exp(ikx)$, where $k >> 1$ is the wavenumber. The problem has been earlier addressed by Alexey Vladimirovich Popov [1] who ingeniously used a combination of Leontovich—Fock parabolic-equation approach, Kirchhoff-type heuristics and Sommerfeld—Malyuzhinets technique to derive an expression for the cylindrical wave arising at the jump point O.
In the course of systematic application of boundary-layer techniques to diffraction by singularities of curvature [4, 5], we investigate Popov's problem through an employment of Fock's parabolic-equation method [2, 3]. This results in an exhaustive description of the outgoing wavefield u^{out} in a neighborhood of O involving novel special functions resembling classical Fock's ones [2, 3].
A support from RSF grant 22-21-00557 is acknowledged.

[1] A. V. Popov, Backscattering from a line of jump of curvature, In: Trudy V Vses. Sympos. Diffr. Raspr. Voln, 1970, Nauka, Leningrad, 171–175 (1971).
[2] V. A. Fock, Electromagnetic Diffraction and Propagation Problems, Pergamon Press, Oxford, 1965.
[3] V. M. Babich, N.Ya. Kirpichnikova, The Boundary Layer Method in Diffraction Problems, Springer, Berlin, 1979.
[4] E. A. Zlobina, A. P. Kiselev, Boundary-layer approach to high-frequency diffraction by a jump of curvature, Wave Motion, 96, 102571 (2020).
[5] E. A. Zlobina, A. P. Kiselev, Short-wavelength diffraction by a contour with Hölder-type singularity in curvature, St. Petersburg Math. J. 33 (2), 207–222 (2022).

AUTHORS INDEX