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Proceedings of International Workshop

"Failure of Heterogeneous Materials under Intensive Loading: Experiment and Multi-scale Modeling"

10-14 February 2014, Perm, Russia

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The conference goals

The conference goal is the discussion of novel approaches in multiscale modeling of advanced materials with meso-, micro- and nanostructure (metals, alloys, ceramics and composites) in wide range of load intensities. Specificities of material responses and damage-failure transitions under dynamic, shock wave loading, high cycle and very high cycle fatigue is characterized by the influence of structure and defect induced mechanisms of relaxation with large scale temporal-spatial dynamics. This assumes the development of molecular dynamic approaches, statistical, mesoscopic and thermodynamic models, methods of structural and experimental verification using "in-situ" registration of temporal-spatial dynamics of structural, kinematic and stress variables. The problems of structural scaling analysis of recovered samples by digital image correlation, atomic force microscopy, high resolution profilometry methods will be discussed in the context of verification of multiscale modeling approaches.

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Contents

The superposition of power-logarithmic and power singular solutions in the two-dimensional elasticity problems

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A new method for determination of power and power-logarithmic singularities of solution for a class of one-dimensional singular integral equations with generalized kernels and complex conjugate unknown function is developed. By analyzing the characteristic part of an integral equation the problem for solution singularity exponent at the end of the integration interval is reduced to group of the independent transcendental equations for this exponent.

A comparison of the results for power and power-logarithmic solution singularities associated with a class of singular integral equations of the two-dimensional elasticity is performed. It was established that additive form (superposition) of the mentioned singular solutions has the singularity exponent which is known for the classical power asymptotic. The parametric approach for equations on real singularity exponent is suggested to extend domain where non-oscillatory asymptotic is implemented.

Numerical results for the two-dimensional problem of the elasticity theory for the crack terminating an interface are represented. Some other fracture mechanics problems on elastic stress concentration at discontinuities are discussed.

Ply-by-ply damage modeling of composite structural elements subjected to low-velocity impact

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Low velocity impact damage of composite structural elements has been simulated using the developed ply-by-ply FE models. The models imitate the impact damage of plates in according with ASTM D7137framework and three stringer panels as well. The applied constitutive material model was identified after corresponding coupon testing. The models allow analyzing of the both intra- and inter- ply damage and failure for prediction of residual strength of the structural elements. The results of the simulation were compared with the impact test data.

Experimental study of morphology of fracture surface of titanium alloys in a high- and gigacycle fatigue

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Fatigue (high- and gigacycle [1]) crack initiation and propagation in titanium alloys with coarse and fine grain structure is studied by fractography analyses of fracture surface. Fractured specimens were analyzed by interferometer microscope and SEM to improve methods of monitoring of damage accumulation during fatigue test and to verify the models for fatigue crack kinetics. Fatigue strength was estimated for HCF regime using the Luong method [2] "in-situ" infrared scanning of the sample surface for the step-wise loading history for different grain-size metals. Fine grain alloys demonstrated higher fatigue resistance for both HCF and gigacycle fatigue regimes. Fracture surface analysis for plane and cylindrical samples was carried out using optical and electronic microscopy method. High resolution profilometry (interferometer-profiler New View 5010) data of fracture surface roughness allowed the estimation of scale invariance (the Hurst exponent [3]) and to qualify the existence of two characteristic areas of damage localization (different values of the Hurst exponent).

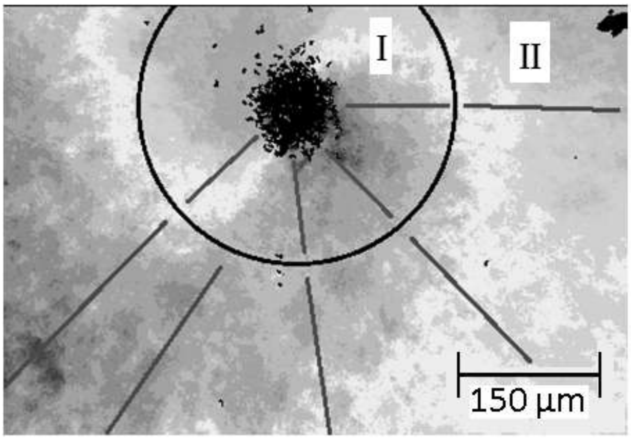

Figure 1. New View 5010 image of fracture surface with two zones of roughness.

Area 1 with diameter ~300 µm (Fig. 1) has the pronounced roughness and is associated with damage localization hotspot. Area 2 has less amplitude roughness, occupied the rest fracture surface and can be considered as the trace of the fatigue crack path corresponding to the Paris kinetics.

This work was supported by projects of RFBR (№13-08-96025, №14-01-31193, №12-01-31145).

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Self-similar behavior of water under electroexplosive loading

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Distilled water was loaded by electrical explosion of copper wire by discharge of energy stored in capacitors [1,2]. Free surface velocity was measured by fiber-optical VISAR system [3]. In order to provide free surface conditions a special probe was developed. It consists of plastic tube with a plastic condensing lens inside. Optical fiber was inserted on the one side of the tube and a thin metallized PTFE film was placed on another. Wave profiles was recorded for different energy stored in the capacitors (W_C=11÷56 J) and for different distance from the wire X_i (Fig.1-A). Analysis of the profiles obtained by processing VISAR data (Fig.1-B) shows us that the first burst in the profile (Fig.1-B,a) is related to the electromagnetic processes in the loading device. The second part of the signal (Fig.1-B,b) is associated with the compression wave. Time interval Δt between these two parts (Fig.1-B) depends linearly on the distance X_i (Fig.1-C). The velocity of the compression wave obtained from the linear fit is close to the speed of sound in the water c^*~1470 m/s with relative error 9%.

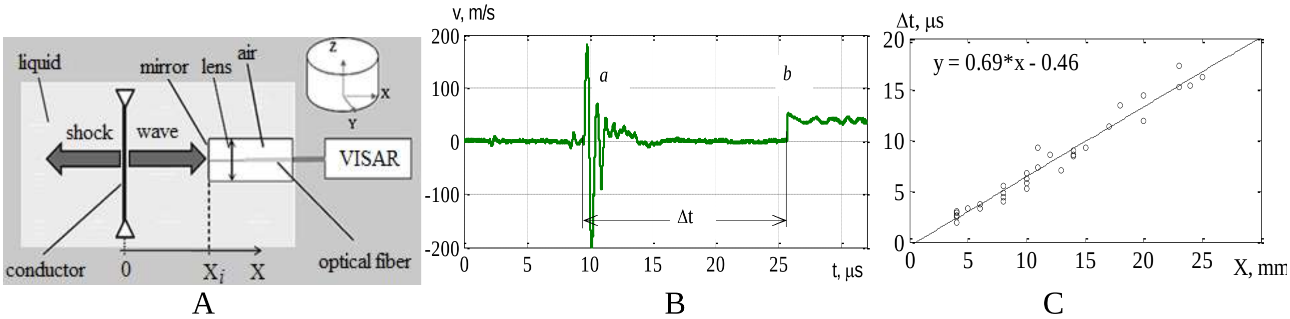

Figure 1. A – The experimental scheme for measurement free surface speed. B – Profile registered by system VISAR, X=25 mm, W_C=28 J. C – Dependence time Δt of the wave travel from distance X.

The typical free surface velocity profiles are shown on Fig.2-A. They are similar to the profiles obtained in [4] for the plate-impact experiment. The spall strength P_S was calculated from the velocity profiles. We found that the spall strength P_S depends on the strain rate $\dot{\varepsilon}$ at unloading part of pulse (Fig.2-A,b-c) as $\dot{\varepsilon}\sim P_S^{0.3}$. Calculating the compression pulse amplitude P_0 (Fig.2-B) from the velocity profile (point b Fig.2-A) and strain rate on the wave front (a-b) we have obtained self-similar relation $\dot{\varepsilon}^*\sim P_0^{3.2}$ (Fig.2-C). The same power law was found for solids in [5,6]. Free surface velocity profiles (Fig.2-D) obtained at the distances X_i=4 mm and Xi=6 mm are different from those for the bigger distances (Fig.2-A). We have observed low-amplitude jump before the main compressive wave front on the profiles (Fig.2-D) which looks like the elastic precursor.

Calculated velocity of this wave front is c_1=1750÷2000 m/s. The nature of this "elastic precursor" is unclear and additional research and experiments are required.

The work is supported by RFBR (№13-08-96025 r_ural_a, №14-01-96012 r_ural_a) and №14-1-NP-332.

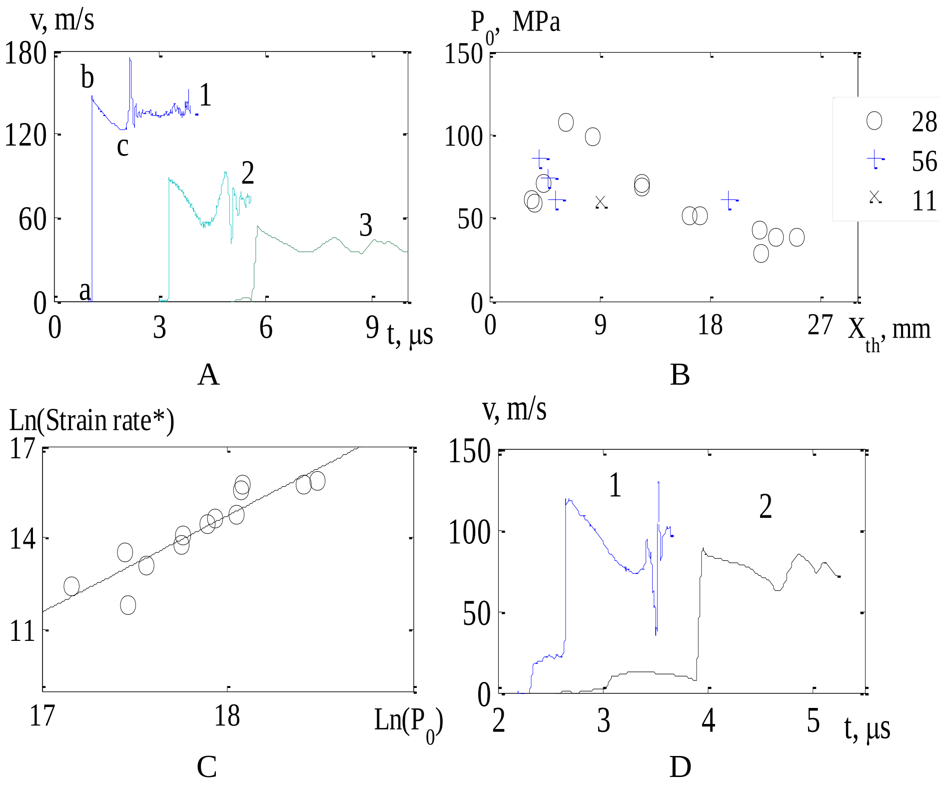

Figure 2. A – Free surface velocity profiles, X_i: 1 – 8 mm; 2 – 14 mm; 3 - 25 mm; (28 J). B –Compression pulse amplitudes at distances $X_{th}=\Delta t\cdot c^*$. C – Strain rate at the wave front versus peak stress, log-log coordinates. D – Free surface velocity profiles: 1 – X=4 mm (c_1=1746 m/s, c_2=1438 m/s, P_0=85 MPa, $\dot{\varepsilon}^*=4.44\cdot10^6\ s^{-1}$, P_S=33 MPa, $\dot{\varepsilon}=2.45\cdot10^{-4}\ s^{-1}$); 2 – X=6 mm ($c_1$=2000 m/s, c_2=1617 m/s, P_0=61 MPa, $\dot{\varepsilon}^*=1.11\cdot10^6\ s^{-1}$, P_S=17 MPa, $\dot{\varepsilon}=1.13\cdot10^{-4}\ s^{-1}$); (56 J).

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Effect of hydrogen on plastic strain localization and fracture of steels

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Previously, we presented experimental data [1] according to which plastic strain development in solids exhibited a localized character over the entire process. This phenomenon is especially clearly manifested on a macroscopic scale, where the patterns of strain localization are related to the deformation hardening operative on the corresponding stages of straining. Embrittlement due to H involves a vast loss of mechanical properties with the following characteristics such as, for example, decrease of ductility and fracture tension with the increase of H concentration. This phenomenon poses a serious practical problem, the solution of which determines the durability and safety of operation of a steel structure. The main aim of this investigation was to elucidate the effect of dissolved hydrogen on the macroscopic plastic flow localization patterns in tensile strained steels.

The investigations were performed for FCC monocrystals of the austenitic stainless steel (*Fe*-18%*Cr*-12%*Ni*) and BCC polycrystals of low-carbon steel (*Fe*-0.07%*C*). The samples had a working part with dimensions of 25·5·1 mm and were tensile strained at 300 K on an Instron testing machine at a mobile clamp velocity of $8.3\cdot10^{-6}$ m/s. The distributions of the plastic distortion tensor components for all points of the sample surface were determined using the method of double-exposure speckle photography [2]. The samples were electrolytically saturated with hydrogen in a thermostatted three-electrode electrochemical cell with graphite anode, operating at a controlled constant cathode potential of $U = -600$ mV (relative to silver chloride reference electrode) in a 1 N sulfuric acid solution containing 20 mg/l thiourea. The hydrogenation was effected at 323 K for 24 h after preliminary purging the solution with nitrogen. The current–voltage curves were recorded using an IPC-Compact potentiostat.

It has been found that the propagation velocity and wavelength of the localized plasticity waves are affected by the strength characteristics of steels, which are determined by the interstitial impurity content *H*. Therefore, the wave patterns of localized plasticity appear to be useful for a detailed analysis of plasticity exhibited by real metals and alloys. The use of such patterns can help derive more exhaustive and accurate information about the processing limits of a material relative to conventional characteristics, e.g. elongation and reduction of cross-section.

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Three-dimensional mathematical model of dynamic and shock wave loading of metals and alloys

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Usually dynamic strength of solids at high strain rate is investigated by analyzing the spall phenomena as reflection of compression pulses from the free surface of the sample. Spall fracture of the materials is very complex. In some cases one could observe multiple spallation as results of several reflections of compression pulses. Present work devoted to the three-dimensional numerical simulation of behavior of metals under dynamic and shock-wave loading. Statistical-thermodynamic approach allowed us to establish the role of the ensembles of defects in the mechanisms of plasticity and fracture. Deformation under intensive loading are linking to the defect induced relaxation process that has qualitative different scenarios depending on the initial structure and strain rates. Structure induced relaxation properties and failure are related to the multiscale dislocation evolution that include the stages of new dislocation substructure nucleation and growth in the presence of external stress and due to interaction with other dislocation and dislocation substructures (mesodefects). The model includes the kinetics for two structural variables - defect density tensor (defect induced strain) and structural scaling parameter, that provide the multiscale description of characteristic stages of damage evolution. The dynamic behavior of ductile materials associates with a specific type of criticality (structural-scaling transition) in microshear ensembles. The self-organization in shear band ensembles and the transformation of shear bands into the damage localization areas are described as the generation of multiscale collective modes in microshears ensembles.

The identification problem for model parameters estimation was carried out on the dynamic tests. The different conditions (tension, shear, compression) of dynamic loading (using split Hopkinson-Kolsky bar tests) are analyzed in terms of long-range correlation properties of collective modes and spatial invariants. Proposed statistical model of mesoscopic defects in solids was implemented in commercial FEM codes Abaqus. Numerical simulation was carried out using this approach. And the verification of model was proposed using shock-wave experiments. Spall fracture is formed in the area of intensive accumulation of defects mostly positive displacement, so the numerical calculations as a criterion was selected the maximum value of the spherical part of the defect density tensor. Numerical results show adequate correspondences with experiments.

The work was supported by RFBR (13-08-96025) and Presidium of RAS Program (12-C-1-1013).

Numerical simulation of the plastic shear localization and failure of metals under dynamic loading

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The research is focused on simulation of high-strain rate loading to study the mechanisms of plastic flow localization and stages of damage-failure transition as the multiscale phenomena in shear band ensembles [1]. The statement corresponds to dynamic shear loading (Kolsky bar torsion test) of hollow cylindrical specimens The self-organization in shear band ensembles and the transformation of shear bands into the damage localization areas are described as the generation of multiscale collective modes of microshears. There are three characteristic stages of dynamic strain localization and damage-failure transition: development a quasi-uniform plastic flow, localization of plastic strain on the characteristic scales and the formation of adiabatic shear bands preceding the specimen failure [2,3]. Model of solid with defects [1] was used to simulate high-strain rate loading. Kinetic equations for numerical integration were:

$$\begin{cases} f(x)\cdot\dot{\sigma} = -\Gamma_1\sigma + \dot{\varepsilon} + \Gamma_2\dfrac{\partial F}{\partial p} - \Gamma_3\dfrac{\partial^2 p}{\partial x^2} \\ \dot{p} = \Gamma_4\sigma - \Gamma_5\dfrac{\partial F}{\partial p} + \Gamma_6\dfrac{\partial^2 p}{\partial x^2} \\ \dot{\delta} = -\Gamma_7\dfrac{\partial F}{\partial \delta} \end{cases} \tag{1}$$

where: σ is the shear component of the stress tensor; ε is the shear component of the strain tensor; p is the shear component of the tensor of microshear density; δ is the scalar structural-scaling parameter; F is the part of the free energy related to the microshear ensemble; $\Gamma_i\,(i=1,...,7)$ are the kinetic coefficients; $f(x)$ is the function which explain elastic deflection of the cylindrical specimen under Kolsky bar torsion test and allows to consider the problem as one-dimensional.

Finite difference method was used for the numerical solution of kinetic equations (1). The result of one of the calculations is shown in Figure 1.

Characteristic stages of dynamic strain localization and failure are linked to the specific kind of loading causing inhomogeneous strain distribution along the specimen and generation of collective modes in microshear ensemble with multiscale temporal dynamics associated with self-similar solutions of evolution equation for microshear ensemble. The features of self-organization as the power law for strain localization area are discussed.

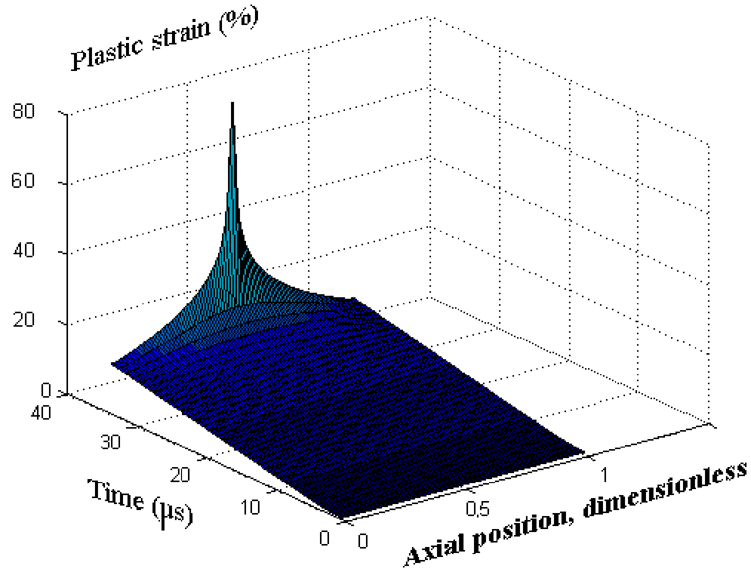

Figure 1. The distribution of plastic strain.

According to the numerical solution, we can see that the first plastic shear strain has quasi-uniform distribution along the sample. Then there is the localization of strain at the characteristic scale. This is followed by rapid growth of plastic strain extending over smaller characteristic times.

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Shock temperature of polymers

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The main methods to investigate the properties and behavior of solids in a wide range of phase diagram are dynamic methods. The basic principles of such methods are described in [1] and they remain basic in our days. Usually only kinematic characteristics of shock process are measured to construct the hugoniot of the material. Relatively small number of methods and investigations are dedicated to direct measurement of thermodynamic parameters, primarily the temperature. The major methods to measure the temperature are optical methods [2].

The report presents experimental data of brightness temperature behind the shock front in several polymers - plexiglass, teflon and epoxy. The shockwaves in samples were generated with the use of D16T aluminum baffle plate and impactor. The thicknesses of the sample, baffle plate and impactor were in the ranges of 5-10, 3-6 and 3-6 mm respectively. All impactors have been accelerated with explosion products to achieve velocities in the range of 3.7-6 km/s.

To measure the brightness temperature a comparison of spectral luminosity was made for the reference source and shock-compressed sample under identical geometry of optical scheme, sensitivity of the photocathode, and photomultiplier amplification. Exemplary tungsten lamp of type TRU 1100 - 2350 has been used as reference which is temperature standard in the visible light range and has emitter belt of 2.5x20 mm^2 size. According to the technical characteristics of this lamp the brightness temperature of emitter is about 2350 K at a current through the lamp being about 30A. A four channel pyrometer has been used. A detailed description of the pyrometer is in [3].

Thermal radiation directly from the behind of the shock front propagates to the beam of waveguides, which transmit the light from the explosion chamber to a photomultiplier. The waveguides were 10 m length and have been located 50 mm from sample surface. FEU-51 with a multi-alkali photocathode (C20 type) was used as radiation detector with the range of spectral sensitivity being 300-750 nm. The back surface of the sample was facing the waveguides, and had been closed with opaque mask with a rectangular aperture size of 2.5×20 mm^2. Diameters of the waveguide containment and quartz core were 0.75 and 0.2 mm respectively, the aperture angle of the input light into the waveguide was ≈ 18 °. Interference filters with lines λ = 550, 630 nm and with a bandwidth of $\Delta\lambda$ = 10, 20 nm respectively have been installed in the measuring channel between the ends of waveguides and photomultiplier photocathodes. To improve the signal/noise ratio, a combined filter KS-S3S (λ = 660 nm; $\Delta\lambda$ = 120 nm) of colored glass and filter of OS-12 glass with a lower bandwidth limit of 560 nm were used. Temporal resolution of recording channel was about 25 ns.

Experimental results are compared with calculation results of models of dynamic deformation of polymers that are based on Maxwell's principles of irreversible deformation. The models consist of conservation laws equations that take into account relaxation of shear stresses during deformation [4]. To complete the model appropriate constitutive relations were constructed. They are: the equation of state with non-spherical deformation tensor and the function of relaxation time of shear stresses from parameters that characterize the medium state. Construction of the function of relaxation time is based on the structural mechanisms of irreversible deformation which is thermoactivated. An example of the application of such principles can be found in [5].

The models was used to predict the stress-strain behavior in uniaxial compression at wide range of strain rates and to solve some problems of shock deformation of polymers. A good agreement has been achieved between the experimental and calculated temperature along the hugoniot of studied polymers.

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Application of aluminum foil sensors for fatigue damage evaluation of carbon fiber composite

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Composite materials, reinforced with carbon fibers, with their superior properties are widely used in the industry, especially in aerospace. But due to the complexity of structure, there are a lot of defect types that might nucleate during operation (matrix cracking, fiber breakage, delamination, etc.). In this regard it is relevant to develop new techniques for strain evaluation under different loading schemes and conditions.

Many recent papers on the subject of non-destructive testing are devoted to Structural Health Monitoring (SHM) systems. Such systems can provide information as the damage occurs and significantly improve the safety of operation.

In the literature an approach described to the monitoring of materials under fatigue is related to the application of “smart sensors” [1]. This method is based on optical registration of images of foil glued onto the specimen surface. Due to the cyclic loading the strain relief on the foil is formed and it is captured by digital camera and then processed to calculate the informative parameters to assess the damage state of the material. The aim of the present study is to evaluate the possibility of application of such sensors for composite fatigue evaluation, as well as to develop a set of informative parameters for image processing.

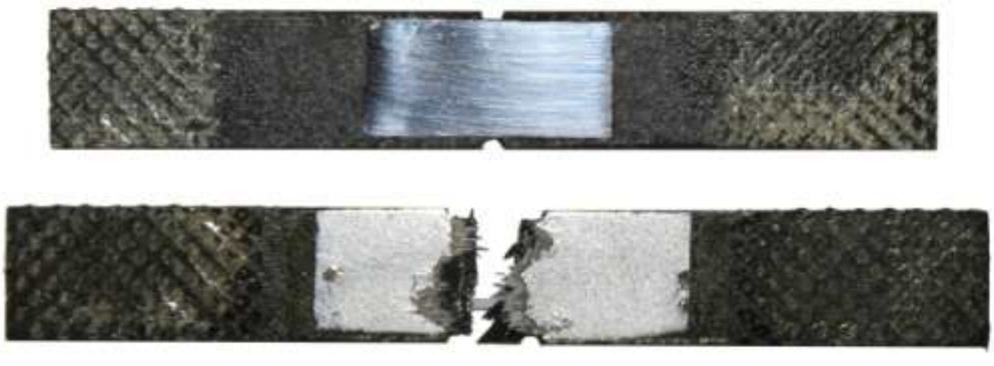

Figure 1. Images of specimens before testing and after failure.

The specimens of carbon fiber composite with foil sensors were tested cyclically using servo-hydraulic testing machine UTM Biss-00-201 and the images of sensors were captured (Fig. 2) throughout the experiment. For quantitative analysis of the obtained foil sensor image series following informative parameters were calculated: Shannon Entropy (H), Mean Square Error (MSE), Fractal Dimension (FD) and energy of Fourier spectrum (FS).

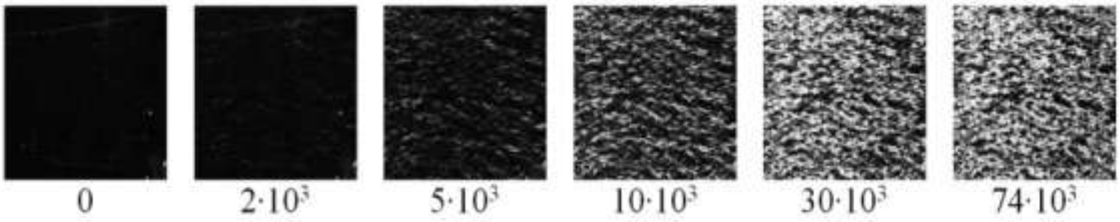

Figure 2. Images of the foil for the various number of cycles

In order to assess the sensitivity of the foil sensors used the 12 cyclic tests were carried out. The upper load was varied and the fatigue failure of the specimens (with the same dimensions) occurred at different lifetimes (Fig. 3): 42K, 75K and 151K cycles.

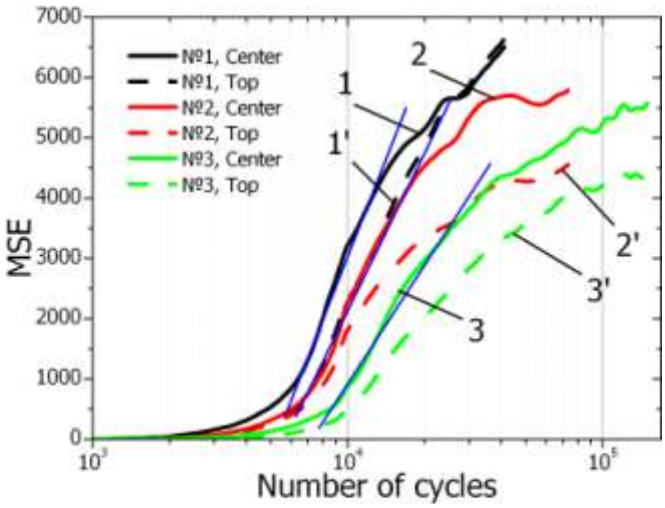

Figure 3. Graph of MSE: the type of the specimen is marked out, dash line corresponds to the top calculation area of the foil, solid corresponds to the central area between notches.

After the analysis of results the following can be concluded:

1. All informative parameters used to evaluate the strain induced relief possess a 3-stage pattern: at the first stage the values remain constant, at the second there is great increase while at the last stage the slight increase up to failure is observed.

2. MSE and H parameters provide better results in contrast with FD and FS. It is proposed to use these parameters as additional ones to primary evaluation.

3. The sensor made of aluminum foil shows high sensitivity to stress concentration in specimen with two edge notches, as well as to different load levels (different number of cycles prior to failure). Thus it is possible to construct the nomographs for specific loading schemes and conditions and to evaluate remaining service life of structures.

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Scaling in fragmentation of brittle materials

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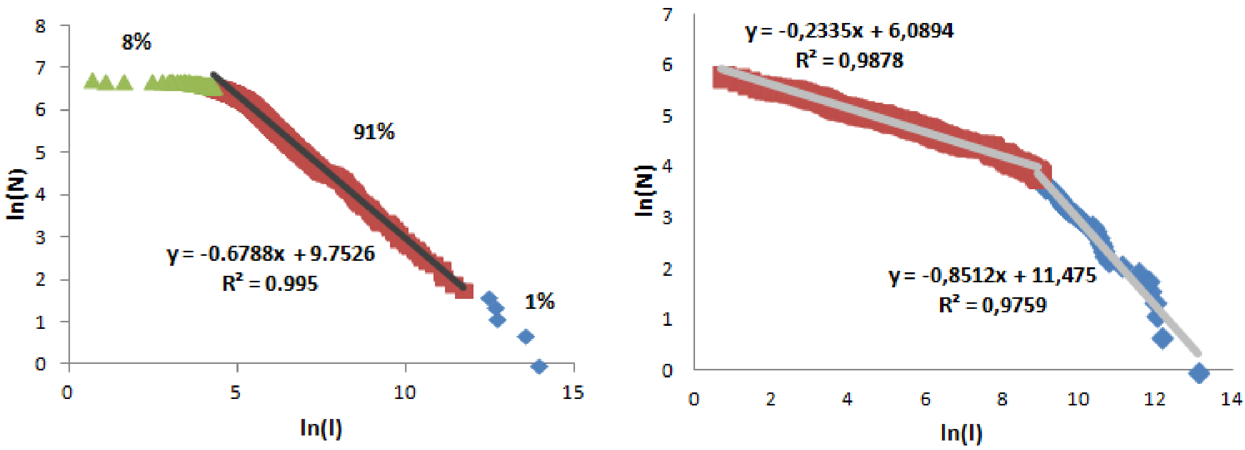
Results of fragmentation processes (the breakup of matter into smaller pieces) are visible everywhere and can be observed in both engineering and natural objects over a wide range of spatial and temporal scales. An investigation was conducted to examine experimentally the process of fragmentation of brittle materials: 1) the fragmentation of glass plates under quasi-static loading; 2) the fragmentation of quartz cylindrical rods under dynamic loading [1,2]; 3) the fragmentation of ZrO_2 ceramic cylindrical sample using Split Hopkinson Bar (SHB) techniques; 4) impact fragmentation of synthetic mineral alloy (syminal). In the quasi-static tests of glass plates, two types of scaling laws were considered. Of these, one was based on the fractal relation similar to the Dielectric Breakdown Model or the Diffusion-limited Aggregation Model, and the other involved the definition of the fragment size distribution. The dynamic fragmentation statistics was studied in the recovery experiments with quartz cylindrical rods. Three types of loading conditions were realized using a ballistic set-up. The results of experiments have indicated that the variation in the sample size and loading conditions does not lead to the change in the type of the fragment size distribution function.



a) b)

Figure 1. Distribution of time interval separating the fractoluminescence impulses: a) quartz sample; b) ceramic sample.

The fractoluminescence-based method was used to measure the distribution of time quantities. Impact loading applied to specimens leads to the formation of fracture surfaces, which produces intensive light emission registered then by Photo Multiplayer Tubes. Both the fragment size distribution and the time interval distribution separating the fractoluminescence impulses show evidence of obeying scaling laws. Experiments on the fragmentation of ZrO_2 ceramic cylindrical samples were carried out using Split Hopkinson bar techniques. The fragment size distribution for ceramic samples, as for quartz ones, is governed by the power law. At the same time, the distribution of the time interval between the fractoluminescence impulses has the critical point separating the plots for small and big intervals, which correspond to different power law exponents (Fig.1). Previously, “syminals” were called “stone casting materials”. The mechanical properties of these materials are similar to the properties of the high strength ceramics. The fragment size distribution of syminal samples showed the power law.

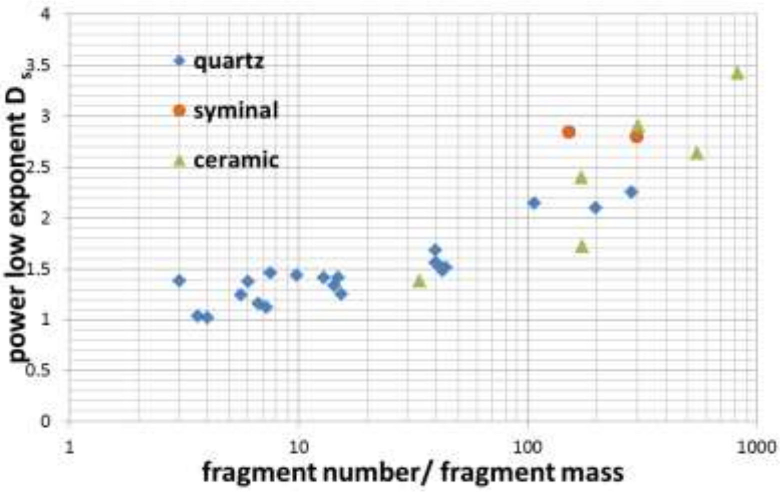


Figure 2. Log-log plot of power lower exponent vs normalized fragment number.

The fact that the fragment size distribution for all brittle materials studied in our investigation exhibits power laws supports the suggestion [3] that for ductile materials the fragment size distribution is described by the exponential function, and for brittle materials – by the power function. Figure 2 illustrates the dependence of power low exponents for fragment size distribution of studied brittle materials on normalized fragment number.

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Synthesis, properties and application of zirconium tungstate

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Materials with anomalous thermal properties find the application in the composite materials technology. Zirconium tungstateis the perspective material due to demonstrates a negative thermal expansion, $\alpha = -9.6\cdot10^{-6}C^{-1}$ in temperature interval -273 - 770^{o}C. ZrW_2O_8 can be used in the technology of composite materials. Introduction the particulates of ZrW_2O_8as reinforcement element into metal matrix allowed to obtain the high strength materials of composite due to difference values of coefficient of thermal expansion (CTE) of matrix and strengthening element. For example, calculations showed that the internal compression stresses generated by the difference of values of the CTE can reached up to 2 GPa as compare with Orowan strengthening $\Delta\sigma$ ~ 20 MPa.

The ZrW_2O_8 was prepared by low temperature decomposition of precursor obtained by hydrothermal method. The starting components for preparing the precursor were aqueous $Na_2WO_4\cdot2H_2O$, $ZrOCl_2\cdot8H_2O$ and HCl. The hydrothermal reaction occurred at 160^{o}Cfor 36 h. The product $ZrW_2O_7(OH,Cl)_2\cdot2H_2O$ was repeatedly washed with distilled water, filtered and dried at 110°C. Finally, when being heated at 570 ^{o}C for 1h the $ZrW_2O_7(OH,Cl)_2\cdot2H_2O$ was transformed into ZrW_2O_8.

The morphology of the ZrW_2O_8 was represented as the rod-shaped particles with a private block structure. It was shown that the formation of the cubic ZrW_2O_8 proceed through the amorphous phase. The crystal structure of synthesized ZrW_2O_8 was determined. The synthesized ZrW_2O_8 demonstrated a negative thermal expansion behavior from 25 to 750 °C.

The structure and mechanical properties of the Al – ZrW_2O_8 composite containing 0.1 - 10 wt.% of zirconium tungstate were studied. It was found that the introduction of 0.5 wt.% of ZrW_2O_8 leads to increasing of mechanical properties of the composites - Hv=284 MPa, σ = 159 MPa as compared with the same properties of pure aluminum.

Response of magnesium single crystals to shock-wave loading

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The main objectives of present study were search for material and slip directions for which the anomalous growth of the dynamic yield stress may be observed. We have chosen magnesium because of a number of factors. The deformation systems in magnesium are governed by its underlying hexagonal close-packed (hcp) atomic structure with a lattice axial ratio r of c/a = 1.624. It has three well known slip systems: basal, prismatic, and pyramidal. Twining makes large contribution into the deformation process when basal slip is hampered. Depending on the orientation of the single crystal with respect to the shock front, it is possible to study dynamic yielding on each system separately. Primary basal slip should be observed if the crystal is shock loaded in inclined direction with respect to the c axis. Secondary prismatic slip is activated for wave propagation along an a axis or in other transversal direction in which case the primary system is subjected to zero shear stress. Tertiary pyramidal slip and twining are activated for wave propagation along the c axis. Thus, there is opportunity to study several deformation mechanisms independently. For analyzing the expected shock-wave data, it is important that temperature dependences of elastic constants of magnesium are known from experiments [1] and ab initio calculations [2]. Finally, magnesium and its alloys are widely used and there are several publications [3,4] on their behavior under shock-wave loading.

Magnesium single crystals 0.2 mm to 3 mm thick were shock loaded along three directions, including crystal axes *a* and *c* and the direction at 45 degrees to the *c*-axis. The samples were grinded and polished mechanically and then chemically with the following annealing at 723 K during 25 min. The plane shock waves in the samples were generated by impacts of aluminum flyer plates of 0.2 mm, 0.4 mm, 0.85 mm and 2.0 mm thickness with the velocity of 630±30 m/s. The flyers were launched using explosive facilities. For experiments at elevated temperatures we used resistive heaters with power up to 1 kW, which enabled to heat the samples up to the required temperature within 10 min or less. The temperature was controlled by thermocouples with ±10°C accuracy. In experiments, the free surface velocity histories were monitored with the VISAR [5].

Shock compression along the *c*-axis causes inelastic deformation by means of pyramidal slip and twinning and is associated with the largest HEL. The easiest basal slip was activated by shock loading along the inclined, off-axis direction and is associated with smallest HEL value. For all orientations, we observed decay of the elastic precursor wave and growth of the HEL values with increasing temperature. However, for the c-orientation the growth is caused by decrease of elastic constants and not with an increase of resolved shear stress along the pyramidal slip planes. In the other orientations the resolved shear stresses in slip planes at the HEL increased with temperature. At inclined shock compression we found two plastic shock waves for which the stress behind the first depends on the peak shock stress. The crystals demonstrate the largest spall strength at shock loading along the a-axis and smallest one at shock loading in off-axis direction.

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Structure and mechanical properties of ZrO_2 - TiC ceramic

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It have been studied a particles morphology, a specific surface and fine crystalline structure of ZrO_2 and TiC powders subjected to ball-milling mechanical activation and properties of ceramic composites based on these powders. It was found that the machining powders in a ball mill reduces the average particle size TiC from 0.6 m^2/g up to 3.4 m^2/g. After 5 hours of machining occurs of zirconia to the destruction of large agglomerates (12 μm) of individual particles (0.3 μm), however, specific surface area while not changing significantly.

It was shown that particles of titanium carbide consist of two phases with different atomic ratio of carbon to titanium $TiC_{0.68}$ $TiC_{0.53}$. Revealed that machining of titanium carbide and zirconia powders leads to a decrease in the coherent-scattering region and increase the level of residual microstresses crystal lattice.

Maximum of density after sintering can be achieved by means of separate ball-milling activation of powders, as compare with the its mixtures. It was shown that addition of 5wt.% TiC, provides a minimum porosity of about 1% and a maximum hardness of 12.5 GPa.

Structure of composites represented by two types of zirconia grains - small order of 1-2 microns, and large order of 5 microns, and titanium carbide grains whose size is 15 microns. Isolated pores are present on the grain junctions in the form close to spherical, the dimensions of which do not exceed 2 μm. A distinctive feature of the structure of ceramic composites $ZrO_2(Y_2O_3)$-TiC is the formation of abnormally large grains of zirconia around titanium carbide inclusions. Accordingly the EDAX analysis it can be assumed that in interfaces between the titanium carbide and zirconia were observed a reaction with formation of oxide-carbide compounds.

Design of Non-conventional Composite Laminates: A Case for Multiscale Computations

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The purpose of this presentation is to provide introductory information about a Center for Research, Education and Innovation (CREI) recently established at the Skolkovo Institute of Science and Technology in Moscow. The Center is called ASPEM, which is the acronym for Advanced Structures, Processes, and Engineered Materials. The primary goal of ASPEM is to provide a holistic approach to product development via integrated materials, design and manufacturing of advanced composites made up of any combination of organic, metallic, ceramic constituents with or without reinforcements. The Center is being build by forming seven functional research units, referred to as labs, each of which will operate over a small range of associated length scale, but will collectively cover a broad spectrum of length scale. These research laboratories are sequenced in the following manner; Engineered Materials Lab, Mechanics of Materials Lab, Nondestructive Testing and Evaluation Lab, Structural Analysis and Design Lab, Simulation of Processes and Virtual Testing, Multifunctional Materials and Structures, Manufacturing and Technology Transfer Lab.

The second part of the presentation will introduce research on design and automated manufacturing of Composite laminates that have non-traditional features. First, design philosophies that shaped up the composite structures development processes based on unique features of modern fiber reinforced composite materials will be discussed. When appropriate the role of multiscale computing in the design process will be emphasized. Next, the concept of non-conventional laminates will be introduced to demonstrate the real advantage of bringing together automated manufacturing together with the design in an integrated fashion to build such layups with innovative features that will allow better exploitation of tailoring potential of composite laminates. A new multi-step design methodology that allows design optimization of large scale composite parts with large number of discrete orientation angles will be introduced. The new methodology makes use of basic material parameters as design variables, which provide a simple way of representing the stiffness properties of a multi-layered laminate with only a few variables. The first stage of the design utilizes a novel optimization scheme based on cellular automata paradigm for continuous design variables using optimality criteria. After obtaining optimal distribution of lamination parameters a guide-based Genetic Algorithm approach is applied in the second step to generate the fully blended solution with discrete stacking sequence. In the last step fiber-paths are generated using fluid flow analogy.

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Study of dissipative characteristics of synthetic mineral alloys by experimental methods

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The mechanism of deformation at impact speeds in excess of 1000 m/s is different from the usual. Often as a result of such exposure occur to change the structure at the crystalline level, so changing the material properties, an examples of changes is to increase the level of amorphous, increas the ability to energy dissipation, etc. [1].

The purpose of research is study the characteristics of the deformation and fracture of synthetic mineral alloys (cast basalt) at high shock-dynamic tests.

Objects were synthetic mineral alloys (cast basalt) system SiO_2-Al_2O_3-FeO, its structure is, the crystalline aggregates complex structure and an amorphous layer is distributed along the boundaries of crystalline aggregates [2].

Experimental studies were held on two unit of equipment: pneumatic installation of high-speed penetration and apparatus for dynamic compressive strength tests.

Table 1. Results of experiments on the high-speed destruction of synthetic mineral sample alloys by using pneumatic equipment.

№ test	Parameters of the punch	Impact velocity, V м/c	Temp T_{max},°C	The point of impact
1	cylindrical shape (L=50mm, Ø5mm, M=7,4g)	650	114	upper
2	cylindrical shape (L=45mm, Ø5mm, M=6,8g)	125	43	middle
3	cylindrical shape (L=45mm, Ø5mm, M=6,8g)	80,6	110	bottom

4	cylindrical shape (L=45mm, Ø5mm, M=6,8g)	49,5	70	middle
5	spherical shape (Ø6mm, M=1g)	65	121	Bottom

Table 2. Results of experiments on the high-speed destruction of synthetic mineral sample alloys by using dynamic compressive strength tests equipment .

№ test	Speed impact of the punch on the rod, V м/c	Temp T_{max},°C	The point of impact	The maximum value of stress, Pa	The maximum strain rate, 1/s
1	22,7	185	upper	$3 \cdot 10^8$	$3{,}0 \cdot 10^3$
2	25	175	middle	$4 \cdot 10^8$	$2{,}5 \cdot 10^3$
3	23,1	101	bottom	$5{,}8 \cdot 10^8$	$2{,}8 \cdot 10^3$
4	24	195	middle	$4{,}3 \cdot 10^8$	$2{,}6 \cdot 10^3$

Equipments were fixed heat the sample back surface by using an infrared camera CEDIP Silver 450M. Results are presented in Table 1 and 2.

The sample was broken depending on the application point of impact. Found that at a strain rate ~ $2.5 \cdot 10^3$ 1/s samples are destroyed into fragments smaller than 0.5-1 mm (size close to the size of crystalline aggregates in the structure). Dependence of the strain rate on the the value of stress has not linear character is predominantly parabolic curves. Temperature surface sample at the moment of fracturing is 40 – 195^{0}C. Heating of the sample is uneven, on the back surface of the sample was found areas with the highest temperature, the higher the impact rate, the greater these areas.

These results characterize synthetic mineral alloys as material with a good capacity for energy dissipation. Upon impact on synthetic mineral alloys, the mechanical energy is transformed into a wave energy, which creates conditions for the structural changes.

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Research of possibility of initiation of synthesis in synthetic mineral alloys under high shock-wave action

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Today, the shock-wave synthesis is pretty much modern technology for create of new materials. Strain rate, the pressure and time of process make fine conditions for untypical deformation mechanism - undislocation. Amorphous and composite materials with a heterogeneous structure, which include synthetic mineral alloys are most susceptible to deformation undislocation mechanism than others.

There are studies on the shock-wave synthesis of powders, but we suppose that monolithic material has great potential for such a synthesis [1].

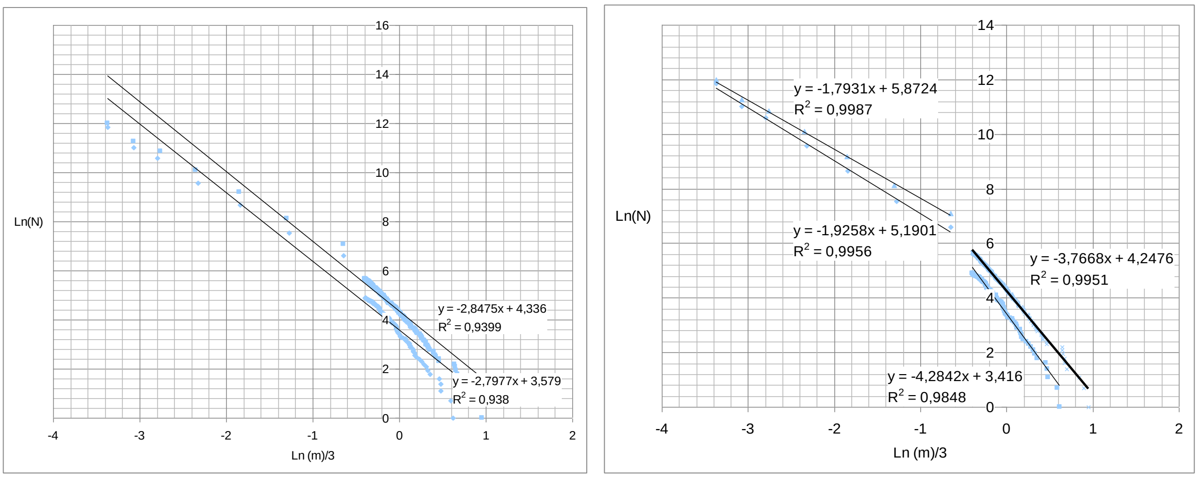
In this article, we presented the results of experimental studies about of the synthesis in synthetic mineral alloy in the monolithic state under shock-wave mechanical shocks on rate 2800-3000 m/s.

The object of research is synthetic mineral alloy based of silica with the addition chromium oxide. Shock-wave actions was made using a punch with rate 2800-3000 m/s, rate of punch was achieved through Electromagnetic Induction Launcher EML (railgun) [2].

Two types of samples were used. Both types of samples had a disk shape with a diameter of 80 mm. The height of the first kind of samples was 33 mm, and the second - 100 mm. The target sample was placed at a distance of 0.45 m from the muzzle of the railgun.

For evaluation of the results was used by fractional analysis, scanning electron microscopy and X-ray microprobe analysis.

Cumulative distribution function of fracture fragments by size are shown in Fig.1. The study by scanning electron microscopy was revealed spherical particles (Fig. 2) among fragments of destruction. These spherical particles are composed of iron oxide according to microprobe spectrum analysis, the structure they are similar to the aerosol particles. Among the fragments of destruction have been found yet amorphous particles and fragments with signs of plastic deformation, while the plastic deformation isn't peculiar for synthetic mineral alloys.



A B

Figure 1. Cumulative distribution function of the target fracture fragments: A - sample D = 80 mm, h = 33 mm at a rate punch V = 2800 m/s, B - sample D = 80 mm, h = 100 mm at a rate punch V = 3000 m/s.

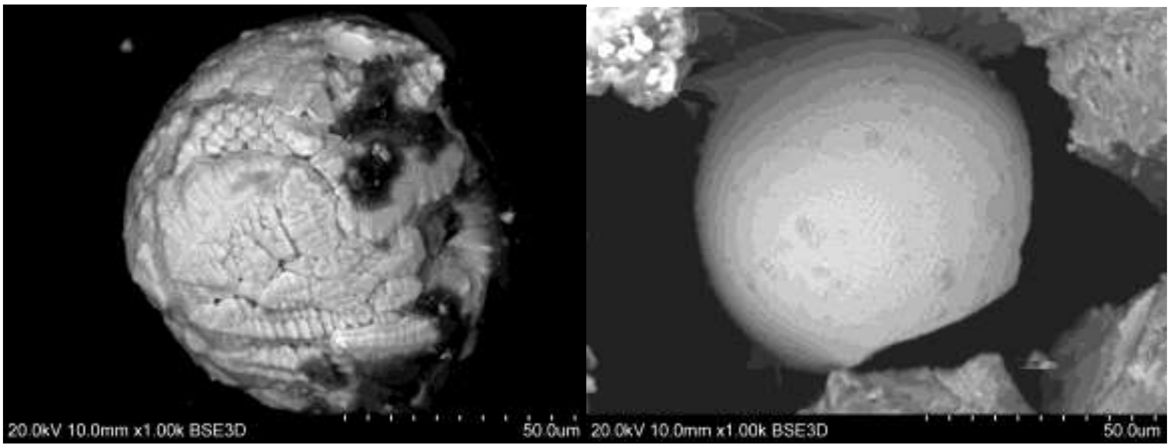


Figure 2. Spherical fragments after shock wave action.

Thereby, research of possibility of initiation of synthesis in synthetic mineral alloys under high shock-wave action in monolithic state by rate 2800-3000 m/s indicated that for these materials is typical ultrafine grinding and changing the crystal structure defects, aerosol formation, amorphization, and beginning mechanism of the plastic deformation. With this action on the material there are "after effects", that is pulverized matter has "excess" energy, that accumulates in the destruction process. Shockwave activation monolithic materials extends the concept of shock-wave synthesis principle.

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Experimental investigation of the heat dissipation energy in fatigue crack tip area in dependence on the fatigue crack rate

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This work was devoted to the investigation of the heat dissipation process under cyclic loading of the steel specimens with a central hole. Applicability of the infrared technique for investigation of the crack propagation was described in details and widely developed in the works of A. Chrysochoos et al. [1, 2]. Original experimental setup (Figure 1) containing infrared camera, Peltier element and potential drop detectors was developed to observe the whole process of energy dissipation occurring in fatigue crack tip area under cyclic loading and to detect the crack size simultaneously.

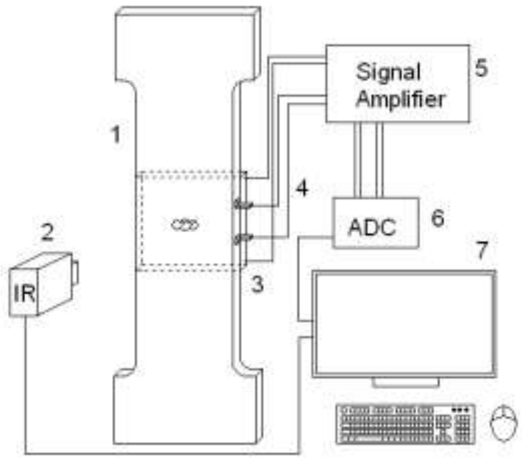

Figure 1. Principal scheme of the developed experimental setup: 1 – specimen under testing; 2 – infrared camera; 3 – Peltier element; 4 – potential drop measuring setup to monitor the crack length; 5 – analog amplifier MDU-8; 6 – analog digital converter ADC NI USB-6251; 7 – PC with LabView software.

To process of the experimental data obtained by infrared camera the original program was used. Processing program contained the procedures of the compensation of the relative motion and filtering of the noise caused by environment (filtration procedure including time and space corrections of the signal). Original algorithm allowed us to reconstruct the heat dissipation field near the crack tip and to calculate the value of the energy dissipated during each cycle of the loading (Figure 2). Additionally to calibrate of the infrared camera and to calculate integral heat flow from the specimen surface the Peltier element was used.

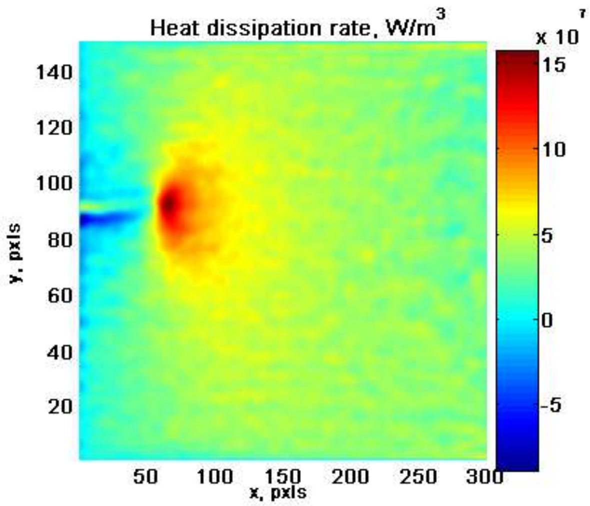

Figure 2. Heat dissipation field obtained by the experimental temperature data and original processing algorithms.

The main goal of this study was to develop the thermodynamic approach for simplification of the Paris law and definition of the relation between heat dissipation and fatigue crack characteristics such as crack length, stress intensity range, crack rate and etc. The dependence between plastic work and stress intensity range was shown by H.P. Strüwe and R. Pippan [3]. In our study we supposed that all plastic work was converted into the heat. Using this assumption and results presented in [3] the relation between heat dissipation rate and fatigue crack rate was obtained experimentally (Figure 3). This result could be used for more deep understanding of regularity of crack initiation and its development in cyclic loading conditions.

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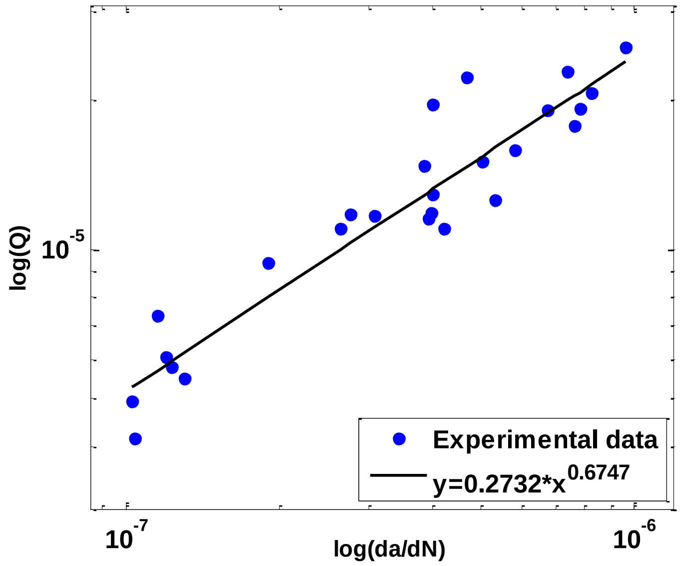

Figure 3. Approximation of the experimental data of the heat dissipation rate and fatigue crack rate.

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Deformation behavior of ceramics with carcass structure

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It has been studied a porous ceramics obtained from ultra-fine ZrO_2 powders. Samples were obtained by pressing and sintering of compacts, the porosity of ceramic samples was from 15 to 80 %. The structure of the ceramic materials was a cellular structure.

A distinctive feature of all the «σ - ε» diagrams obtained in the experiment was their nonlinearity at low deformations which was described by the parabolic law. Restructuring of deformation diagrams in double logarithmic coordinates allowed to determine the value of the exponent in deformation equation from experimental data. The increase of porosity in ceramics was accompanied with the increase of exponent, this fact may be associated with the change of deformation mechanism. The obtained values of the exponent for ceramic samples with a porosity higher than 25 % amounted to 3.5, which is probably due to a major contribution of the mechanical instability of ceramic cell elements in the ceramic carcass in the deformation process.

The studies found similarity in the mechanical behavior of high-porous cellular foam plastic and porous ceramic with cellular structure based on zirconium dioxide. This fact indicates that the observed nonlinear elasticity for low deformations on deformation diagrams is due to mechanical instability of the cellular elements in the ceramic carcass.

It has been studied the deformation behavior and mechanical properties of contrast materials which represented ceramic carcass with inserted gel component.

Modeling inelastic deformation of duplex steels at high temperatures

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The purpose of this paper is to examine the two-phase polycrystalline metals and description in physical hardening slip systems multilevel models of inelastic deformation, based on the explicit introduction of internal variables. The work deals with two-phase austenitic-ferritic (duplex) steel, which in recent decades have been widely used in the petroleum refining, pulp and paper, pharmaceutical, chemical, food industry and many other fields found. The paper rises the problem of hardening strength relation which are written based on the analysis of the physical structure of the material, taking into account the interactions of mobile dislocation with forest dislocations, Lomer-Cottrell barriers and grain boundaries. It should be noted that the increase in temperature leads to a decrease of the critical stress for slip system - softening of material related to the duplex steels processes recovery in the ferrite phase and recrystallization in the austenite phase.

The paper considers the two-level statistical model that is based on a physical approach. The element of macro-level is macro-volume containing a large number of meso-level structural elements (grains, subgrains, fragments). Connection between the elements of meso-and macro-level is achieved by using the Voigt hypothesis. With multi-level approach macro stress state can be obtained in two ways - by averaging with the meso-level, or using the constitutive equations on the macro level. To avoid this ambiguity the procedure of matching constitutive equations is used and also the variables of adjacent scale-levels.

The next point concerns physical approach is used to build models of inelastic deformation of mono-and polycrystals, based on the formulation of constitutive relations, hypotheses and the main provisions of which rests explicitly consider the mechanisms of deformation at the meso-and microscale, defining the material behavior at the macro level. In physical theories the main mechanism of inelastic deformation of plasticity is the movement of edge dislocations, that have been confirmed by numerous experiments. At high homologous temperatures as a result of thermal fluctuations on the steps and kinks, which have a dual significance for the motion of dislocations . On the one hand, the dislocation line length increases, thereby increasing the resistance to movement of dislocations. On the other hand, steps and kinks are elements of the fine structure of dislocations to facilitate overcoming the barriers of different nature within the crystallite. Increase in temperature leads to the activation of diffusion processes and the special influence of point defects on dislocation mobility. Lowering the temperature reduces the stacking fault energy and the appearance of split dislocations, which in turn lead to the occurrence of twinning dislocations and dislocation barriers nature. Thermal motion can lead to an increase in the intensity of the interaction of dislocations with each other and other defects in the crystal lattice.

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Computational study of the dependence of effective mechanical properties of ceramics based on metal nanocrystal oxides on partial concentrations of different sized pores in its structure

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The pore structure of the ceramic material is characterized by the presence in it of pores with different sizes. Pore size distribution function of these materials contains several (in the simplest case of two) maxima. The height and width of each maximum determine a fraction of pore space corresponds to pores with the proper size.

Thus, the materials with a bimodal pore size distribution function and with a certain value of the total porosity can be characterized by a great number of combinations of pore structure parameters: volume ratio of pore space corresponding to the pores of the first and second peak of the function. In this aspect, said material is no longer just a porous body, but it is a construction. The mechanical behavior and properties of this construction are determined by the specified parameters of its structure. In practice, the combination of the parameters of the pore structure and mechanical properties of the material largely determine the scope of its functional application. It does knowledge about the mechanical properties of material in the entire range of these pore structure parameters very actual and required. Thus, in this paper, a numerical study of the dependence of the strength and elastic properties of ceramic materials on the fraction of pore volume corresponding to pores of the second maximum of the pore size distribution function in the total porosity of the material was carried out.

Calculations were based on multiscale approach, developed in the framework of the of movable cellular automaton method (MCA) [1]. Plane MCA-model of ceramic ZrO_2 (Y_2O_3), with a pore size comparable with the grain size and bimodal pore size distribution function [2] was developed. Considered material with round pores. On the basis of computer calculations an analytical estimation for numerical dependence of strength and elastic properties of material under compression loading on its total and partial porosities, corresponding to pores with different size, was found. It was shown that the strength of brittle materials containing pores of two different sizes are defined as the value of total porosity and the value of partial porosities corresponding to one of the maxima of the of pore size distribution function. The difference in the strength of such materials with the same value of total porosity, but with different number of pores with different size can be up to 50%. Effective elastic modulus of the material are determined only by the value total porosity.
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Numerical study of deformation and fracture of ceramic composites based on nanocrystalline metal oxides in the framework of movable cellular automaton method

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In the framework of movable cellular automaton method (MCA) [1] a multiscale model of ceramic composites based on nanocrystalline metal oxides with phase transformations in their structure during mechanical loading was developed. On the basis of developed model the mechanical behavior of ceramic composites based on nanocrystalline oxides of zirconium and aluminum with different contents components under uniaxial compression was investigated. For numerical investigations 2D square specimens with the size 32 mkm were generated. The volume content of each component was varied from 20% to 80%. At the interface between components assumption of perfect contact conditions was made. Mechanical properties of the model material corresponded to that of nanocrystalline ceramics ZrO_2 (Y_2O_3) and Al_2O_3 with a porosity of 2% [2]. The speed of loading was 0.5 m/s. The problem was solved under plain strain conditions. Accounting for phase transitions in the model was carried out under the proposed phenomenological approach, implying the formulation of the law of inter-automaton interaction corresponding to the irreversible behavior of the material. This law has been chosen so as to correspond to qualitative and quantitative deformation diagrams of ZrO_2 (Y_2O_3) with structural transformations. An increase of fracture toughness of zirconia ceramics under implementation of phase transitions were taken into account by introducing a pair of automaton transition kinetics from the "linked" state to the "unlinked" one. To do this, the crack propagation rate parameter was explicitly introduced at the MCA method. It was capable to slow down the transition of automaton pair to "unlinked" state for several time steps. Usually in the MCA method this transition occurs at the one time step, which corresponds to crack propagation with the speed of longitudinal sound. In this model (for the pairs automata modeling phase transition), the value of crack propagation velocity was lower than the velocity of sound in the material. Within the framework of the model constructed main mechanisms of deformation and fracture of composites were studied. The interrelation of structure, mechanisms of fracture and effective strength and elastic properties of the composite was shown.

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Numerical simulation of the storage energy process

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It is now well known that real metals have complex structure, which is a hierarchy of different levels. The structural evolution observes at all scale levels and leads to irreversible deformation and destruction during deformation process. To develop a model of defect evolution under plastic deformation we have to choose the basic physical level of the material microstructure description and to describe the geometry of the elementary defects.

One of the possible ways to describe the defect kinetics is the statistical model of the defect ensemble. This model should take into account the stochastic properties of a defect initiation, their nonlinear integration and link between microplasticity and damage accumulation properties. Description of the defect evolution based on the kinetics of two parameters: the first parameter is a second order defect density tensor which can be considered as a deformation caused by the defects; the second one is a scalar parameter depending on the ratio of two characteristic scales (the mean size of defects and mean distance between them), it characterizes the susceptibility of the material to the defect growth in the deformation process [1].

This model lets us to describe the energy balance in the material during plastic deformation process, to obtain the constitutive equations of the defects evolution and make possible to evaluate the value of the stored energy which appears in the material due to the defects evolution of the different structural levels [2]. The efficiency of the constitutive equations is shown by the simulation of quasistatic deformation process of steel and iron.

Numerical simulation was carried out in the finite-element package Simulia Abaqus 6.13 with the use of a subroutine UMAT. The obtained results showed that the model can be used for the stress-strain state description and for the homogeneous stored energy simulation.

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On the development of carbon nanotubes arrangement in polymers and ceramics

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Since the intriguing properties of carbon nanotubes (CNTs) there have been managed many attempts to use them as dopants in different materials such as polymers [1,2] or ceramics [3,4]. Operating properties of such nanocomposites are totally determined by the quality of dispersion of CNTs in the material matrix and the adhesion between dopants and material. Because of strong van der Waals interactions between CNTs it is not easy to make their proper dispersion, and probably that is the reason of such contradictory in literature concerning the effect of CNTs on the mechanical, heat- and electro-conductive properties of such polymer or ceramic nanocomposites. If only the problem of arrangement of CNTs would resolved, manufacturing of materials with outstanding mechanical, electro- and heat-conductive properties would be possible. The most encouraging way of research is to induce some kind of orientation of CNTs in the material, i.e. anisotropy. The current work presents some results concerning this problem.

According to recent knowledge it is preferable to create CNTs ordered structures in liquid or gas medium as well as to use the electric or magnetic field as orientation factor. Therefore in our work in the case of polymer matrix direct or alternating voltage was applied to the cell with mixture of CNTs and liquid polymer (PDMS) in order to obtain more or less anisotropic arrangement of CNTs in the material. Appearance of conductivity in initially non-conductive polymer can be linked with formation of some kind of anisotropy in CNTs system among polymer chains. However results of SEM- investigations and nanoindentation of samples indicate more probable formation of several percolation clusters rather than regular structure of oriented CNTs in polymer matrix. The reason for that is a huge gap between electric properties of CNTs and polymer.

In the case of oxide ceramics electrophoretic deposition of nanocomposite layers from zirconium hydroxide sol with CNTs was performed in both AC and DC voltage applied regimes. DSC – analysis and Raman-spectroscopy of obtained layers in initial state as well as after sintering has revealed strong influence of CNTs on regularities of sintering and final structure of ceramics, namely, CNTs effectively stabilize high temperature tetragonal phase of zirconium oxide. Investigation of mechanical properties of obtained ceramics nanocomposites is the subject of our further research.

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Localization of plastic flow in metals with pores and inclusions

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Localization of plastic flow often accompanies the dynamic deformation of metals [1]. The developed localization reveals itself as an appearance of local areas with high plastic deformation – much higher than in surrounding material. These areas of high plastic deformation usually have a form of narrow bands (adiabatic shear bands); they are two-dimensional and almost flat formations, which boundaries are displaced, one relative to another, like in the cracks, but material between the boundaries remains continuous. The plastic flow localization can be a preliminary stage of material failure; therefore it should be analyzed in terms of material strength.

Our previous numerical investigations [2,3] had shown that various heterogeneities in material provokes localization. Heterogeneity acts as a stress concentrator and initiates more rapid plastic deformation in areas with higher shear stress. The heterogeneity can be a perturbation of dislocation density or any pore or inclusion in the material. Present report is dedicated to a detailed numerical investigation of the plastic flow localization in metals around pores and inclusions, as well as to investigation of influence of the pores and inclusions on the dynamic shear strength.

Simple shear and shock loading of 2D metallic samples with square cross-section are simulated with use of dislocation plasticity model [4,5]. The samples have a pore or an inclusion of different metal in its center. Some results of simulations are presented on Fig.1 and Fig. 2. The both types of heterogeneities initiates non-uniformity of plastic deformation (the localization) on the length scale much longer than its size (see Fig. 1). Inclusion of harder material creates the plastic intensity distribution, which is inversed relative to the case of pore (Fig. 1). Simulations reveal not very high influence of the pores or inclusions on averaged shear stress, but this influence grows up with deformation (Fig. 2); results are for volume fraction of pore or inclusion equal to 3%.

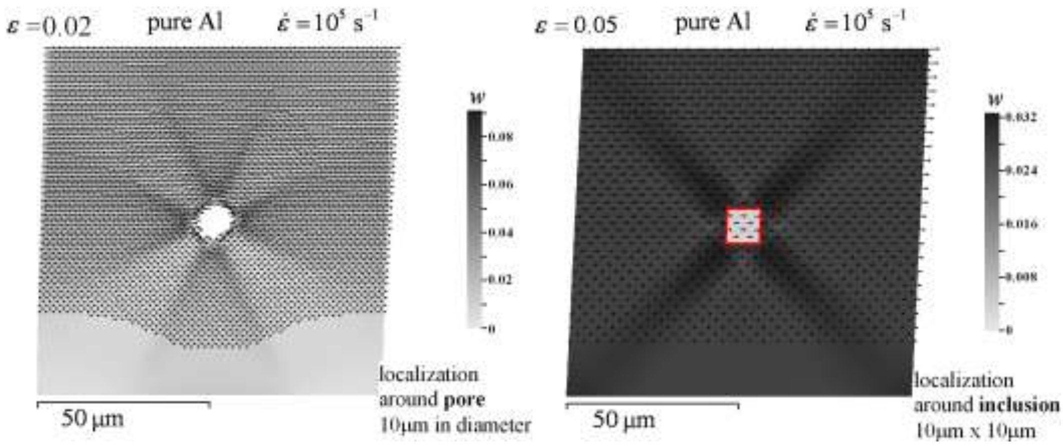

Figure 1. Localization of plastic flow in aluminum around a pore (left panel) and around a copper inclusion (right panel): high-strain-rate simple shear; w – intensity of plastic deformation.

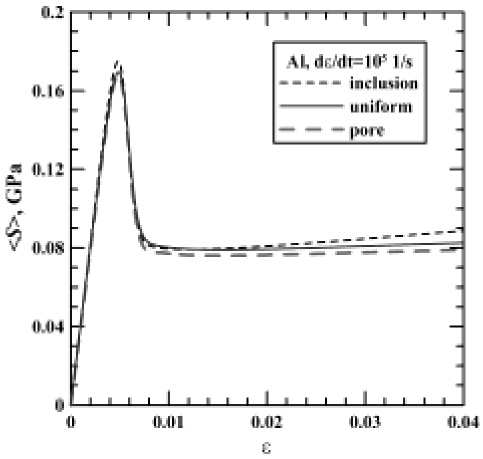

Figure 2. Influence of pores and inclusions on average shear strength of aluminum. Shear stress intensity averaged through the sample as a function of current deformation.

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Tensile strength of metal melts with initial pores

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Tensile fracture of metal melt takes place, for example, under the action of intensive ultra-short irradiation, electron or laser. An isochoric heating can be realized if the pulse duration τ is much less than the typical relaxation time, which is R/c_s, where R is the particle range in substance and c_s is the sound speed. For laser irradiation it means $\tau < 10^{11}$ s^{-1} [1], and for electron irradiation $\tau < 10^9 \div 10^7$ s^{-1} depending on electrons energy [2,3]. In these conditions a metal layer under irradiated surface is rapidly heated and melted by irradiation and becomes the metal melt at high temperature (of about several thousands of K) and high pressure (of about several GPa). Consequent expansion of this metal melt creates, in turn, tensile stresses in it and makes it metastable. The expanded metal melt can suffer a phase transition from liquid to vapor through the formation of vapor cavities in it. Growth and coalescence of vapor cavities lead to fracture of the melt and to the material ablation in the form of mixture of liquid drops and vapor [4]. Therefore, theoretical description of the tensile fracture of metal melt is substantial for the problems of intensive irradiation.

In uniform liquid cavities can be nucleated as a result of thermal fluctuations. In this situation the tensile strength of metal melt (Fig. 1) is determined by surface tension, first of all. Meanwhile, the target material often has different heterogeneities, such as pores. If these pores remain after melting, they can be the cavitation centers at tension and can considerably decrease the tensile strength.

In present report we numerically investigate the influence of initial porosity of metal on its tensile strength after melting. For simulations we use our previously developed computational model of cavitation and tensile fracture of metal melt. This model treats the metal as a two-phase medium which can be a singly connected liquid with (or without) vapor cavities - on the first stage of evolution; and a singly connected vapor with liquid drops - on the last stage. Thermo-fluctuation nucleation of cavities and they viscous growth are considered, as well as the energy and the mass exchange between phases. The model can predict the dynamic tensile strength of metal melt (Fig. 1) and can describe processes in irradiated metal and sizes of metal particles [4] ablated from the irradiated surface. In present investigation, as opposed to previous one, initial porosity of metal is also considered, and its influence on the tensile strength is analyzed.

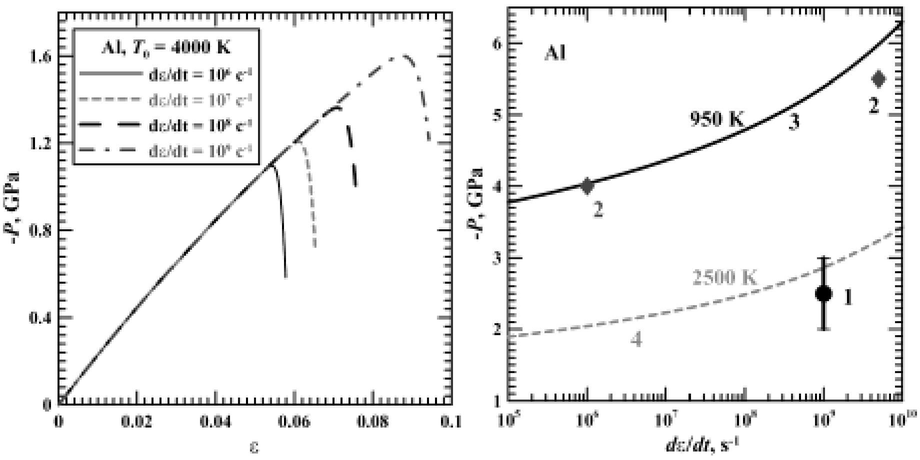

Figure 1. Simulation results for uniform tension of liquid aluminum without pores: pressure versus current deformation (left panel) and maximal achieved negative pressure (dynamic tensile strength) versus strain rate at deferent temperatures (right panel). Markers: 1 – the experimental result [5]; 2 – the molecular dynamics simulations [6] for corresponding temperatures. The surface tension coefficient is taken from [7].

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Relaxation effects in shock-wave processes

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In the shock compression of the condensed matter there is a relaxation of a number of parameters (the shear stresses, thermal streams, etc.). In the report on the basis of model of a Maxwell-like elastic-viscous body some of such relaxation processes are considered, which not account in the analysis of experimental data can lead to wrong quantitative results and incorrect qualitative conclusions.

Allocation and attenuation of an elastic precursor, including a case of motion a shock compressed matter (secondary compression) are among analyzed processes. Other relaxation process – a relaxation of shear stresses in the front of a shock wave, which is directly connected with width of a zone of shock transition. The analysis shows that width of the front of a stationary shock wave depends on strength characteristics of a material.

The role of relaxation processes in the transitional phenomena arising in thin layers – the isolating laying which is using at installation in samples of sensors, using to pressure measurement in shock waves is very essential. The proximity of acoustic impedances of materials of laying doesn't exclude emergence of the relaxation process connected with a rupture of shear stresses. Asymmetric reaction of the sensor of temperature concerning the direction of passing of a shock wave is explained by a relaxation of shear stresses also.

The essential role is played by relaxation processes at interaction of shock waves with a catching-up wave of unloading. Their features are considered on the example of an one-dimensional task about interaction of a flat shock wave with a catching-up wave of unloading.

At impact on materials of intensive power pulse (laser radiation, an ionic or electron beam) the shock wave is formed as a result of intensive evaporation and thermal expansion of matter. In these cases the relaxation of a thermal stream and limitation (extremity) of speed of heat transfer can play an essential role. Relaxation effects in such processes are considered on the basis of the formulated model of the termo-elastic-viscous matter including the hyperbolic equation of heat conductivity.

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Macroscopic manifestations of non-uniformity in irreversible deformation of polymeric materials

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Modern methods of materials behavior investigation are based on the consideration of irreversible deformation mechanisms on different structural levels. It is known that from the standpoint of continuum mechanics irreversible deformation is often regarded as uniform on macroscopic level, but non-uniformity in irreversible deformation connected with structure inhomogeneity and deformation mechanisms implementation always exists on microscopic level. In certain conditions non-uniformity in irreversible deformation existing on micro- and mesoleves can appear on macroscopic level, e.g., in the form of well-examined jerky flow phenomenon (Portevin – Le Chatelier effect) and negative strain rate sensitivity of the flow stress in crystalline and polycrystalline solids. As for polymeric mediums frequently having amorphous structure, microscopic manifestations of non-uniformity in deformation had already been studied [1 – 4]. It has been reported [5] about macroscopic manifestations in irreversible deformation of polymers in the form of jerky flow established for the first time by authors of present work.

The results of investigation of polymeric materials jump-like deformation are dealt with and discussed in the report. The experiments are carried out using a material testing machine Zwick TC-FR100TL.A4K with an electric drive, a system of automatic control, and an ability to extract the results to personal computer. Test operation is realized at a steady loading speed. Deformation diagrams for polymethylmethacrylate (PMMA) and polytetrafluoroethylene (PTFE) are obtained in compressive tests of cylindrical specimens in a wide range of strain rates. The detailed analysis of jerky flow areas observed on deformation curves has shown that at a low strain rate the areas have stress jumps at three scale levels at least. In this case, the jerky flow nature is not chaotic since there is some regularity in a jumps period. The consideration of the areas, where instability appears, has shown that every deformation curve for PMMA obtained at different low strain rates has two deformation ranges containing areas of jerky flow. Regions of stress jumps existence at different scale levels are defined on the strain – strain rate plane. Also, statistical analysis of stress jumps observed on deformation diagrams is carried out. Distribution histograms of normalized jumps amplitudes are constructed. The behavior of histograms changes from close to uniform to bell-shaped having biased peak which can be approximated by lognormal distribution as strain rate changes. The analysis of statistical data has shown that there is power dependence between amplitudes of stress jumps and increments of deformation. This suggests the scale invariance of jump-like deformation of polymers investigated. To put it another way the phenomenon of jump-like deformation has a self-similar nature. The connection between the macroscopic manifestations of micro structural non-uniformity and mechanisms of irreversible deformation of polymeric materials is discussed.

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Multiscale collective properties in defect ensembles and self-similar aspects of damage-failure transition under fatigue and dynamic loading

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Novel tendencies in the study of damage-failure transition are related to the development in situ experimental techniques and methodologies to couple with multiscale modeling and simulation to interrogate and properly interpret material response over a hierarchy of lengths and scales. That is germane to unit processes of defect nucleation, mesoscopic response involving many body defect fields and collective modes of defects involved in the processes of damage localization. The ability to measure at each scale concurrently in space and time and over a range of localizations to obtain sufficient sampling of stochastic responses is paramount. Experimental methods for currently increasing material responses in space and time in large range of load intensity correspond to the process of damage-failure transition as out-of equilibrium phenomena. In this case experiments can be used to quantify deterministic and stochastic parameters for models at critical scales including initial and evolving character of microstructure interfaces and properties. Even when the modeling characteristic critical length and scales it is necessary to carry out simulations over somewhat larger scales to compare with experiments for purpose of validation of properties that are relevant to design. Accordingly, it is necessary to build models that have variably resolution/fidelity capability to decompose domain of space and time. The coupling of in situ dynamic experimental measurements with modeling and simulation constructs the bridging of characteristic length and time scales and provides the understanding and prediction of cooperative material response across the micro-, meso- and macrostructural scales. Application of novel experimental methodologies can be used to validate computational approaches in order to bridge the characteristic length and time scales and to identify the set of material characteristics microstructure attributes and material properties/responses that govern failure phenomenon over a hierarchy of characteristic scales of evolving microstructure or mesostructure.

Statistical theory of evolution of typical mesoscopic defects (microcracks, microshears) revealed specific type of criticality – structural-scaling transitions and allowed the development of phenomenology of damage-failure transition based on the definition of non-equilibrium free energy of solid with defects. The key results of statistically based phenomenology are the establishment of characteristic multiscale collective modes of defects responsible for relaxation and failure. These modes have the nature of the solitary wave and blow-up dissipative structure, provide the mechanisms of damage-failure transition and can be excited in the resonance regime at the corresponding loading conditions. High resolution experiments and structural study in terms of scaling invariance supported the linkage of the evolution of these modes with material responses in large range of load intensity (dynamic crack propagation, resonance excitation of failure under dynamic loading, crack path under high cycle (HCF) and very high cycle (VHCF) fatigue) and allowed us to propose the interpretation of the following effects:

(i) Nonlinear crack dynamics and the transition from the steady-state to the branching regime of crack propagation. The existence of two critical velocities, three characteristic regimes of crack dynamics as the precursors of fragmentation;

(ii) Spatial-temporal scaling of fragmentation dynamics (self-organized criticality);

(iii) Resonance excitation of damage localization and failure in spall condition (dynamic branch under shock wave loading) and failure wave initiation;

(iv) The link of defect induced scaling and scaling laws of fatigue crack path under HCF and VHCF, qualitative changes in the scenario of damage-failure transition near fatigue threshold and VHCF of fine grain materials.

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The problem of internal crack initiation on forged Ti-6Al-4Mo titanium alloy in VHCF

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Recent investigations on the loading regimes for military and civil aircraft engines have shown that Very High Cycle Fatigue (VHCF) loading conditions could be realized in different structural elements of turbine due to transient airflow dynamics [1, 2]. According to Cowles [3], VHCF loading conditions leads to change the crack nucleation mechanisms compared with high cycle fatigue (HCF) regime. Longer fatigue life corresponds to lower stress/strain amplitudes which are not enough to realize a needful level of local plasticity and crack nucleation under plane stress conditions. Thus, crack initiation in VHCF regime is related to the problem of local microplasticity, which is often encountered around different internal imperfections of material microstructure. Therefore, mechanism of crack initiation in VHCF regime is associated to the peculiarities of certain materials and technological processes. For example, in case of industrial materials with relatively low solidification temperature (like steels), non-metallic inclusions are the most common typical imperfections of the microstructure. In case of industrial materials with higher solidification temperature (like titanium alloy), the situation becomes more complex, because there is not any non-metallic inclusion, which could lead to incompatibility in strain-stress states between the matrix and typically harder inclusions. Thus, 'imperfections' of such materials should be related to features of solidification process which could produce different morphology of micro-structure with different crystallographic orientation. Particularly, in case of titanium alloys, it has become clear that the manufacturing process may create macro-zones, that are macroscopic areas of the microstructure with similar crystallographic orientation. The role of such macro-zones is still discussed. Therefore, technological process and heat treatment history (i.e. thermomechanical history) may have a significant influence on the fatigue strength of titanium alloys.

Present research project is focused on the problem of fatigue failure of aeronautical titanium alloy Ti-6Al-4Mo under VHCF loading. Real technological production process used for compressor disk fabrication was examined with regard to the induced VHCF strength. Series of specimens for ultrasonic fatigue tests were machined from a real aircraft compressor disk in different directions: axial, radial and circumferential. Axial specimens were cut from the rim part of the disk. Two types of tests, tension-compression (R= -1) and tension-tension (R= 0.1) were performed. Results of investigation on axial specimens have shown that the scatter in fatigue life for Ti-6Al-4Mo could reach 10^3 cycles. An additional investigation on fracture surfaces have shown, that so large scatter could be associated to different crack initiation mechanisms. As noted above, activated mechanisms are related to peculiarities of titanium microstructure. In case of forged titanium alloy several typical crack initiation sites are observed. Most of them are related to redistribution of alloying elements within certain region. In case of significantly large region of elements redistribution (tens of micrometers), the fatigue life has a tendency to be shorter (10^6 – 10^7 cycles). In this case a crack nucleation could be explained by incompatibility in strain-stress state between such formation and matrix. In case of high localization of element redistribution (several micrometers), fracture surface shows a facet-like fracture pattern at crack initiation site. Such mechanism has a tendency to be activated after higher number of cycles, but also exists for relativity short fatigue life (10^7 cycles). As mentioned above macro-zones have also an effect on fatigue crack initiation and, especially, on the crack propagation process. The influence of macro-zones seems to be less critical for (R= -1) loading conditions; these macro-zones become a more critical parameter for crack initiation mechanism in case of R=0.1.

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Scaling invariance of fatigue crack growth in aluminum alloy

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The role of the collective behavior of defect ensembles at the crack tip and the laws of fatigue crack propagation in aluminum-magnesium alloy have been studied under conditions of symmetric tension–compression gigacycle loading at 20 kHz using ultrasonic fatigue testing machine (Shimadzu USF2000). 3D New View 5010 interferometer profiler high resolution data of defect induced roughness in the crack process zone under fatigue crack path revealed the existence of two characteristic scales: the scale of the process zone and the correlation length that is the scale when the correlated behavior of defect induced roughness has started [1].

The surface relief of fracture surfaces in deformed samples was examined by NewView 5010 interferometer profiler and characterized in terms of the roughness index (the Hurst exponent). The microstructure of fracture surfaces in aluminum alloy samples showed scaling invariance features in terms of the Hurst exponent. The constant value of the Hurst exponent is indicative of a self similar scenario in multiscale damage accumulation and fatigue crack propagation gigacycle regime. The constancy of the scaling index in a broad interval of spatial scales, which includes the scales of evolution of the typical defects, leads to a conclusion that the kinetics of fatigue crack propagation can be considered within the framework of specific class of criticality phenomena [2] that describe the fatigue fracture as multiscale damage-failure transition scenario.

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On some features of fracture behavior of human dentin at different scales

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Human dentin is the multilevel biological composite material, which is the hard basis of a tooth. This hard tissue consists of organic and inorganic phases. There are three scale levels in the structure of dentin. The first is collagen fibers and calcium hydroxyapatite in the nano-crystalline state. The second is network-like structure of collagen fibers in intertubular dentin. And the third is dentin tubules surrounded by a highly-mineralized cuff. Experiments have shown that deformation behavior of human dentin varies from highly deformable to almost brittle in dependence of geometry of applied stress (the ratio between tensile and compression stresses). The brittle behavior is observed when the level of tensile stress is maximal and, vice versa, dentin samples exhibit highly elastic-plastic response when the level of compression stress is maximal. On both microscopic and mesoscopic scales fracture mode of human dentin is similar to ductile FCC-metal. There is extensive plastic zone ahead of crack tip, where satellite pore like cracks are observed. On the contrary, its fracture behavior on the macroscopic level depends on dentin tubulars orientation and the stress distribution in sample. Fracture surface is smooth, when the sample fails in the plane normal to dentin tubulars. In other cases, fracture surface is rough. The shearing test confirms that ultimate strength of dentin in the plane, which is normal to dentin tubulars, is minimal.

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Mechanical properties and energy dissipation traits of ultrafinegrained aluminum alloys under dynamic deformation

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The investigation of mechanical behavior of ultrafinegrained (UFG) and coarsegrained (CG) Al-Mn and Al-Zn-Mg-Cu alloys under dynamic compression by Kolsky-Gopkinson method were carried out. The dynamic mechanical properties of the materials were determined during tests at a strain rate range 10^3 s^{-1}. By infrared scanning the temperature of the samples was registered during compression, then the share of dissipated energy was calculated as ratio of the energy transformed to heat to the energy expended to the deformation. To determine the regularities of energy storage and dissipation in UFG and CG samples their structures were investigated before and after compression. UFG samples were produced by dynamic channel-angular pressing (DCAP). It was shown that DCAP loading conditions (strain rate and accumulated strain) effect on structure formation mechanisms and mechanical properties of the alloys [1]. The structures with different characteristics (structural fragments size, the share of fragmented and recrystallized structure and the level of internal stress, the share of low-angle and high-angle boundaries) were investigated. Structural sensitivity of dissipated anergy and inverse strain-rate sensitivity of the dynamic yield strength of UFG alloys were found.

It was found that the UFG alloy have a greater dissipation ability than CG one. The energy dissipated in UFG alloy rises with increasing of preliminary accumulated strain causing development of fragmentation process during DCAP, a growth of internal stress and dislocation density. As a result of dynamic compression UFG nonequilibrium structure transforms to equilibrium state. In the CG alloy dynamic deformation activates crystallographic slip. As a result subgrained structure (300 nm) with low-angle boundaries is formed. On account of a beginning of fragmentation process a storage energy value in CG alloy is higher than in UFG alloy. UFG alloy having fragmented (subdivided) structure dissipates up to 18% more elastic energy than that having mixed structure contained dynamically recrystallized grains.

In the alloy with fragmented structure the evidences of dynamic recovery due to grain-boundary sliding are observed after dynamic compression. The alloy with recrystalized structure undergoes plastic deformation by dislocations slips, which increases the share of storage energy during compression.

It was established that the difference in the value of dynamic mechanical properties of UFG and CG alloy is 10-20%, while during quasistatic tensile tests UFG alloy exhibit high strength that 2- 2.5 times higher than strength of CG alloy. Under dynamic compression in the UFG A7075 alloy an inverse strain rate dependence of the dynamic yield stress was found out. The dynamic yield stress decreases by 30% with increasing strain rate in the range 4-6 10^3 s^{-1}.

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Thermodynamical model of submicrocrack evolution under cyclic loading

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It is now well known that real metals have complex structure, which is a hierarchy of different levels. Under deformation process the structural evolution observed at all scale levels and leads to irreversible deformation and destruction. To develop a model of defect evolution under small stress amplitude we have to choice of the basic physical level of description of the material microstructure and describe the geometry of the elementary defects. Analysis of the experimental results of the study of structural levels of plastic deformation and fracture [1,2] and resent experimental investigation of damage evolution of fine grain metals can hypothesize that scale level with the size of submicrocracks 0.1-0.3 mm plays a key role in this process [3]. The failure process includes both the nucleation of new microcracks and their development. The contribution of these processes in the failure varies depending on the structure of the material conditions of its loading.

The defect kinetics is different near specimen surface and in the bulk. The rate of microcracks nucleus initiation in the surface layers of one to three orders of magnitude higher than in the bulk material. It is also well known that for high concentration the defect ensemble exhibits both collective and nonlocal effects.

One of the possible descriptions of defect kinetics is the statistical model of defect ensample. This model has to take into account the stochastically properties of defect initiation, their nonlinear integration and link between micropalsticity and damage accumulation.

The data obtained from systematic studies of defects evolution, carried out at Physical technical institute named after A.F. Ioffe RAS shows that the volume defects (submicrocracks with characteristic size about 0.1 mkm) play the important role in deformation process [3]. These defects emerge at the early stage of deformation and effect on the microplasticity and failure processes. The same situation could be observed under cyclic loading. The best materials for the experimental proofing of this hypothesis are the fine grain metals which contained the high concentration of volumes defects (micropores) after manufacturing procedures (equals channel pressing).

The value, geometrically representing the real microcracks with allowance made for a variety of their shapes, sizes and arbitrary orientations as well as or the crack initiated material loosening, can be introduced in terms of the dislocation theory. The description of the model is presented in [4,5].

This work is devoted to the development the model if defect kinetics in the application to cyclic loading of metals. The statistical description was developed based on the mean field approximation of defect interaction and allows us to investigate the effect of initial nucleus concentration of defect evolution process and determine the equilibrium state of materials with defects. Based on the results of solution of the statistical problem we introduce a new thermodynamic variable and derive the constitutive equation for metals with submicrocracks. The proposed constitutive equation applied for the description of defect kinetics near specimen surface and in the bulk. The model allows us to describe the shift of crack initiation location from the specimen surface to the bulk and numerically obtain dual S-N curve for 2023 T3 aluminum alloys. The numerical results have a good agreement with experimental data presented in [6].

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Evolution of the structure and properties of ceramic materials based on ZrO_2 after cyclic thermal shock tests

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Ceramic materials are widely used in the fields of technology where necessary resistance to high temperatures. Due to resistance to aggressive environments and intense high-temperatures shock most promising materials are heat-resistant ceramic materials based system ZrO_2-MgO. However, it remains unclear question of the effect of cyclic thermal shock tests effects on the structure, phase composition and properties of ceramic materials.

Influence thermal tests is studied at cooling in water from temperature of 1000 ^{o}C on structural and phase transformations in nanocristal ceremics on the basis of ZrO_2, partially stabilized in high-temperature updatings by cations of replacement Mg^{+2}. Ceramics differed quantity of a modifying additive magnesium oxide in solid solution ZrO_2-MgO, and, as consequence, a parity of shares high-temperature and low-temperature modifications of a dioxide of zirconium. Independently of quantity magnesium oxide in a solid solution to quantity increase thermal tests in ceramics there was a disintegration of solid solution ZrO_2-MgO, however even at almost full exit MgO, ceramics kept ability to resist thermal shock.

It is shown that increasing the number thermoshock tests influences led to a redistribution of the phase composition on the initial state of ceramics. Already after the first thermal loading on x-ray diagrams increase intensity of the reflections of low-temperature monoclinic fase ZrO_2 and decreasing intensity of the reflections of high- temperature cubic modification ZrO_2. Increasing the amount of monoclinic phase under cyclic loadings thermoshock was the result of a solid solution ZrO_2 - MgO - all in the diffractograms of the samples after several thermal loading reflexes appeared MgO.

After thermal tests in the samples of all the compositions observed a decrease in the size of CDD cubic modification ZrO, was shown. The reason for this could be an increase content of monoclinic ZrO_2, accompanied by significant compressive stresses due to an increase in the cell volume at the phase transition of high- to low-temperature modification of zirconium dioxide, which leads to fragmentation of the crystallites of the cubic phase.Found that thermal cycling did not affect the mechanical properties of ceramics. This may indicate that formed during quenching monoclinic phase does not affect the mechanical properties, due to relaxation of stresses arising in the phase tetragonal- monoclinic transition due formed on the surface of the screen cracks.

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The influence of particularities of inner structure and temperature on the Hugoniot elastic limit and the spall strength of copper

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The effects of growth of Hugoniot elastic limit (HEL) in copper due to changing of inner structure by severe plastic deformation (SPD), preshock loading and admixtures of the fullerene C60 or increasing of initial sample temperature under shock-wave loading are discussed. The character of dynamic deformation and fracture, and also the quantitative characteristics of these processes: the pressure of shock compression, the HEL, spall strength, etc were determined from the analysis of free surface velocity profiles of the samples loaded, recorded with the laser Doppler interferometer system VISAR [1,2].

In this work, the original polycrystalline copper with a grain size up to ~110 μm, copper samples after SPD by overall forging with the average grain size of ~30 μm and submicron grain sizes of ~0.5 μm were investigated. Besides, the influence of preliminary single shock compression on strength properties of the copper samples with grain size ~110 μm was investigated. The part of the experiments was made with the samples, subjected to preliminary SPD in the shock wave of ~35 GPa. In experiments, shock loading pulses with an amplitude up to ~9 GPa were generated in the samples by the impact of flat aluminum plates, accelerated with the explosive device up to 600 – 650 m/s. The measurements demonstrate that the reduction of the average grain size in copper M1 samples from 110 μm up to 30 μm and 0.5 μm leaded to the strength growth in ~1.5 times. The preliminary quasi-isentropic and shock compression of the samples with the grain size of ~30 μm and ~0.5 μm leaded to decrease of copper strength. The homogenous ultra fine-grained samples demonstrated the highest strength, closed to the copper single crystals strength.

For investigation of the influence of carbon admixtures on the strength properties of metals, the HEL and dynamic tensile strength measurements of pressed copper samples with admixture of the fullerene C_{60} by 2-5 wt % under shock-wave loading of ~6 GPa in intensity were carried out. It was found, that the copper samples with admixture of 2 wt % fullerene demonstrate multiple increase of the HEL in comparison with the commercial copper and it equals 1.35-3.46 GPa for such copper samples in dependence on their porosity. The spall strength of the samples with fullerene decreased about tree times.

To investigate the influence of temperature on copper strength properties, the HEL and the spall strength of the polycrystalline commercial grade copper and of the single crystal copper of [100] and [111] orientations were determined for the sample temperatures varying from 293 to 1353K (T_m = 1356 K). The differently preheated samples with thickness between 0.5 and 2 mm were shock-loaded by the copper plates of 1-mm thickness accelerated up to 300-400-m/s velocity in the 58-mm smooth bore gas gun.. The samples of polycrystalline copper demonstrate significant, 9-fold, growth of the stress at HEL between RT and a close vicinity of T_m. Unlike other metals [3 - 8] this type of copper maintains a very high spall strength near melting point; it is only twice as low as that of the copper at 0.85 T_m. The single crystal copper (of both the orientations) also demonstrates a substantial spall strength at 0.94 T_m (1273K). At the same time, the increase of the stress at HEL with temperature in these samples is much weaker than that found for polycrystalline samples of copper.

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Numerical study of vanadium spall strength

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The goal of this research is the modeling of metals behavior under shock wave loading using the structural-statistical model. The important part of numerical study is the verification procedure of model, in this case it was carried out using VISAR data of plate impact loading of the Vanadium target.

The mathematical problem of the collision of two plates (elastic projectile and the Vanadium target) was considered in the statement of plate (one-dimensional) impact [1] in the range of pressure amplitude less than 10GPa. The system of differential equations that corresponds to the statement of plate impact experiment consist of the pulse and mass conservation laws; the equation defining the assumption concerning the total strain rate as the sum of elastic and plastic strain rates, and strain rates induced by the defects kinetics; stress and strain variables as the sum of deviatoric (index d) and isotropic (index s) parts; the Hook law in the “rate form”; the constitutive laws describing the links of stress-strain relation, damage kinetics and the kinetic equation for structural scaling parameter δ, which defines the sensitivity of material structure to the damage accumulation. The presentation of defect induced strain (defect density tensor) as the sum of deviatoric and spherical parts allowed one to describe the influence of the shear and bulk defects on relaxation (plasticity) and damage-failure kinetics as qualitative different scenarios depending on the nonlinearity of thermodynamic potential in different ranges of structural-scaling parameter δ. The spall failure occurs generally due to the generation of the bulk defects that allowed us to formulate criteria of spall failure related to characteristic nonlinearity of damage evolution leading to the blow-up self-similar kinetics at the final damage stage.

The system of equations was solved numerically by finite difference predictor-corrector method using the commercial code MATLAB.

The results have shown that the model describs characteristic profiles of free surface particle velocity, including the formation of elastic precursors, plastic wave front, the generation of “spall” pulse and the reverberation of pulse in the spall plate [2].

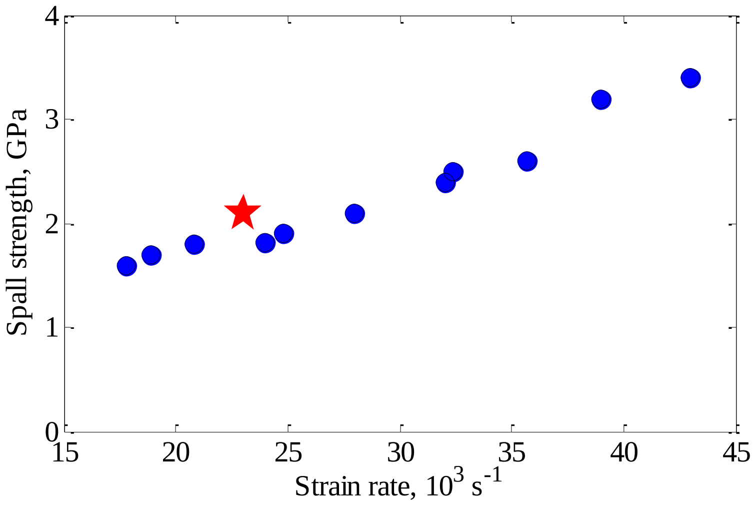

Figure 1. Spall strength versus strain rate: the marker “circle” is result of simulation, marker “star” is experiment.

The calculation of spall strength using the difference between the velocities for plastic stress amplitude and the minimum of particle velocity corresponding to spall pulse was carried out. It was established that the spall strength has changed with stress (or strain rate) amplitude (Fig. 1) [3].

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Elastic-plastic properties and strength of spark plasma sintered ultrafine ceramic WC-Co under shock wave loading

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The objective of this study was to measure the Hugoniot Elastic Limit (HEL) and spall fracture of spark plasma sintered ultrafine WC-Co hard ceramics samples with different content of Co under high-rate compression and tension.

The investigated samples were produced as follows: WC DN 4-0 powder was mixed with varying contents of Co particles of 500 nm in size in 6 planetary ball mill for 500 min using the milling process [1]. The mixed powders were consolidated via the spark plasma sintering process described in [2] with a sintering temperature of 1250°C and an isothermal step length of 5 min. By this method nearly fully-dense samples with a diameter of 20 mm and an approximately height of 5 mm were processed. To produce binderless WC samples the WC powder was sintered directly with the spark plasma sintering process at a temperature of 1800°C and an isothermal step length of 3 min [3]. These samples had the similar dimension as the WC-Co samples. SEM micrographs of the investigated samples with varying Co contents are shown in Figure 1.

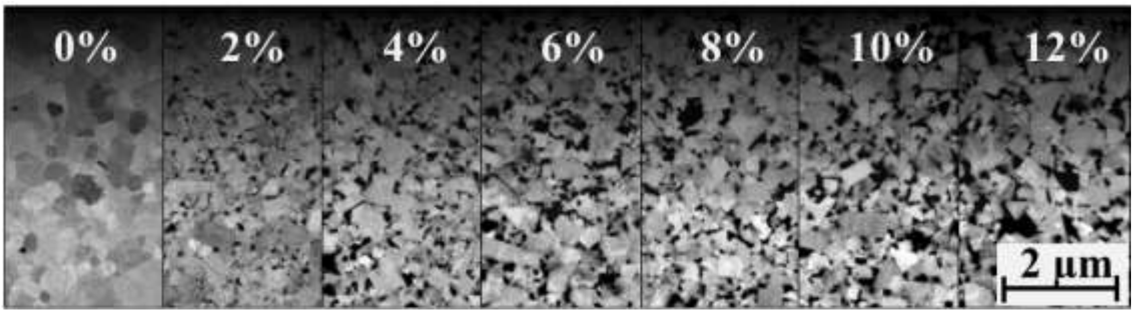
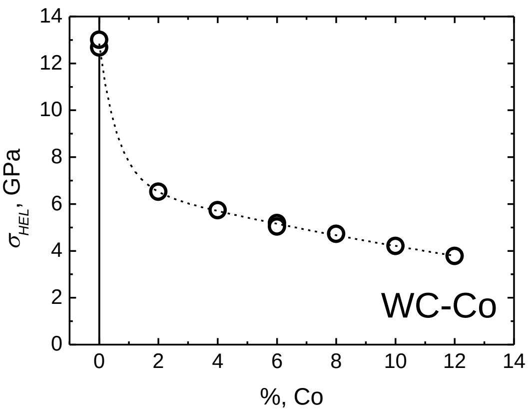
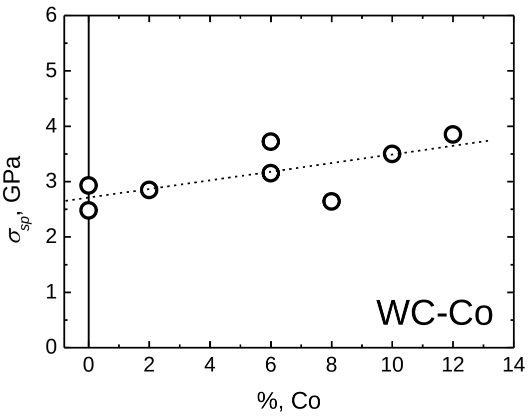


Figure 1. SEM images of the materials with different contents of Co.

In this work, the samples were loaded by an impact of 2 mm thick aluminum flyer plate with a velocity of 1.8 km/s through an aluminum base plate 2 mm in thickness. The base plate was used for cutting off the air shock wave formed ahead of the impactor. The impactors were launched with the use of explosive devices [4]. In our experiments, we recorded the free surface velocity histories $u_{fs}(t)$ of the sample as a function of time. The measurements were taken using the VISAR laser Doppler velocimeter [5] with a time resolution of 0.8 ns in the configuration used.



A



B

Figure 2. Dependence of the Hugoniot elastic limit of WC on the contain of cobalt (A); dependence of the spall strength of WC on the content of cobalt (B).

In the figures 2A and 2B the results of experiments are shown, namely the dependences of the HEL and spall strength of WC on the cobalt content. As it is seen from these figures, the samples without Co demonstrate the maximal value of HEL. The value of the HEL is smoothly decreasing with increasing of the Co content. A big difference in HEL of ceramic samples with concentration of Co between 0 and 2 % is possibly connected with the method of samples fabrication. Spall fracture increases with the increasing of the Co concentration, what is the evidence of the growth of the viscosity of the ceramics with Co.

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Fracture surface features for Ti-based alloys in Low- and Very-High-Cycle-Fatigue regime

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Titanium alloys experienced in-service wide range of external loading with different frequency in dependence on designed structural components. In aircraft structures there very intensive using titanium alloys in compressor disks and rotor blades for gas-turbine engines. Disks and blades manufactured from Ti-6Al-4Mo alloys by the different technology because external loading conditions for them realized respectively Low- (LCF) and Very-High-Cycle-Fatigue (VHCF) regime. In both considered aircraft components used titanium alloys with two phases (α+β)-structure having dominant lamellar or globular shape respectively for disks and blades.

In accordance with introduced earlier bifurcation diagram for fatigued metals, LCF regime directed to damage accumulation on the macro-scale level while VHCF regime related to micro- or nano-scale level for material cracking.

The discussed two different regimes for metals fatigue cracking were considered applicably to titanium alloys VT3 (Ti-6Al-4Mo-3Cr) using bar specimens of 5mm in diameter manufactured from titanium compressor disks for LCF tests and VT8 (Ti-6Al-4Mo) used for manufacturing rotor blades experienced in-service fatigue cracking in VHCF regime. Specimen tests in LCF regime with frequency 1 Hz were performed on the MTS equipment.

Tested specimens and in-service fatigued rotor blade were investigated on the scanning electron microscope EVO-40 of Karl Zeiss firm with using special device for X-ray analyses of material local chemical composition.

In LCF regime there were discovered two types of fracture surface patterns. First, there was quasi-brittle cracking α-phase in the case of crack propagation along the fibers introduced in material structure during disks forging. Between performed mesotunnels along fibers there crack propagated in the perpendicular direction to fibers with fatigue striations formation. Second, there was performed layered fracture surface with alternation areas with and without fatigue striations. The second case related to fatigue crack propagation in the perpendicular direction to material fibers.

X-ray analyses have shown that fatigue striations or quasi-brittle cracking by the α-phase take place in the same material which has not “Mo” in this phase. Consequently fracture surface patterns, fatigue striations or quasi-brittle cracking, can be realized in deformed titanium alloys in dependence on residual plasticity only. Material has self-organized behavior during forging and realized under stamp layered structure with alternating high and low plasticity that directed to different mechanism of cracking, respectively, with or without fatigue striation formation.

In-service fatigued blade of VT8 titanium alloy had subsurface crack origination from several quasi-brittle cracked α-phase facets. X-ray analysis by these facets has shown the same material state that was discovered for VT3 alloy, without “Mo”. Nevertheless X-ray analyses by the material slice, prepared in perpendicular direction to the fracture surface throughout the origin area, have shown that in volume around origin there “Mo” not exists in α-phase. On the distance 1 mm and more, out of the origin, there exists “Mo” in α-phase. Consequently, in the considered case “Mo” has influence on the crack subsurface origination in the investigated blade. But it is not enough for crack origination in VHCF regime because of in-blade very low designed stress level.

Special experiment was performed for blades resonances considering in wide range of influenced frequencies from air stream. The blade of designed shape (large chord) has different types of resonance as was discovered during performed investigation. In some rare cases there was only one type of resonance with blade bending. But in many cases there were two and three neighbored resonance by the bending and torsion Modes. In other cases there were discovered not depended blades vibrations by two forms. Therefore, material subjected to multiaxial in-flight loading with simultaneously tension (because of disk rotation), bending and torsion. It was discovered that one of the resonance takes place in area of crack origination. The minimum frequency for the blade bending resonance in area of crack origination related to 1950 Hz.

Performed investigations of titanium alloys in LCF and VHCF regimes have shown that there exists similarity in fracture surface pattern for them inspite of failure can be resulted of two causes: bad material state (residual stresses) or wrong metals chemical composition.

Quantum Field Theory Evaluation of the Stress States of Grains in Polycrystalline Materials

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Most of inorganic structural materials (metallic alloys, ceramics, minerals etc.) are polycrystalline aggregates, consisted of macroscopically large quantity of single-crystal grains (crystallites). The mechanical behavior of the specimen of polycrystalline material is governed by the physical and mechanical processes in the grains and interaction of the grains. Thus the deformation of polycrystalline material is a cooperative phenomenon typical for condensed matter physics and mechanics of heterogeneous materials. The passing of these processes depend on many parameters, including stress states of individual grains and its evolution during macrodeformation.

In this paper we note a mathematical analogy between the equations of the mechanics of heterogeneous polycrystalline materials and the equations of quantum theory of scattering particles. This analogy allows to apply the methods of quantum field theory to solution of the equations of solid mechanics for heterogeneous media. It is considered the application of Corringa-Kohn-Rostoker method [1], used in quantum theory for calculating wave function $\psi(\vec{r})$ of electrons in metallic alloys from equation

$$\psi(\vec{r}) = \psi_0(\vec{r}) + \int_V d\vec{r}_1 G(\vec{r} - \vec{r}_1)\left[\sum_{i=1}^{N} w_i(\vec{r}_1)\right]\psi(\vec{r}_1),$$

where w_i - potential of electron interaction with *i*-th impurity atom, *G*- Green's function of Schrödinger equation, for evaluating the strain (and stress) field $\varepsilon_{ij}(\vec{r})$ in polycrystals, governed by equation

$$\varepsilon_{ij}(\vec{r}) = \varepsilon_{ij}^{*} + \int_V d\vec{r}_1 g_{ijkl}(\vec{r} - \vec{r}_1)\left[\sum_{\xi=1}^{N} \lambda_\xi(\vec{r}_1)\left(C_{klmn}^{(\xi)}(\vec{r}_1) - \langle C_{klmn}\rangle\right)\right]\varepsilon_{mn}(\vec{r}_1),$$

where $C_{klmn}^{(\xi)}$ - elastic moduli tensor of ξ-th crystallite, g_{ijkl} - Green's tensor.

This method allowed, for instance, to calculate probability density function for stresses in grains under arbitrary macrodeformation of polycrystal. Figure 1 represents this probability distribution of normal stresses under macroshear for polycrystalline zinc [2]

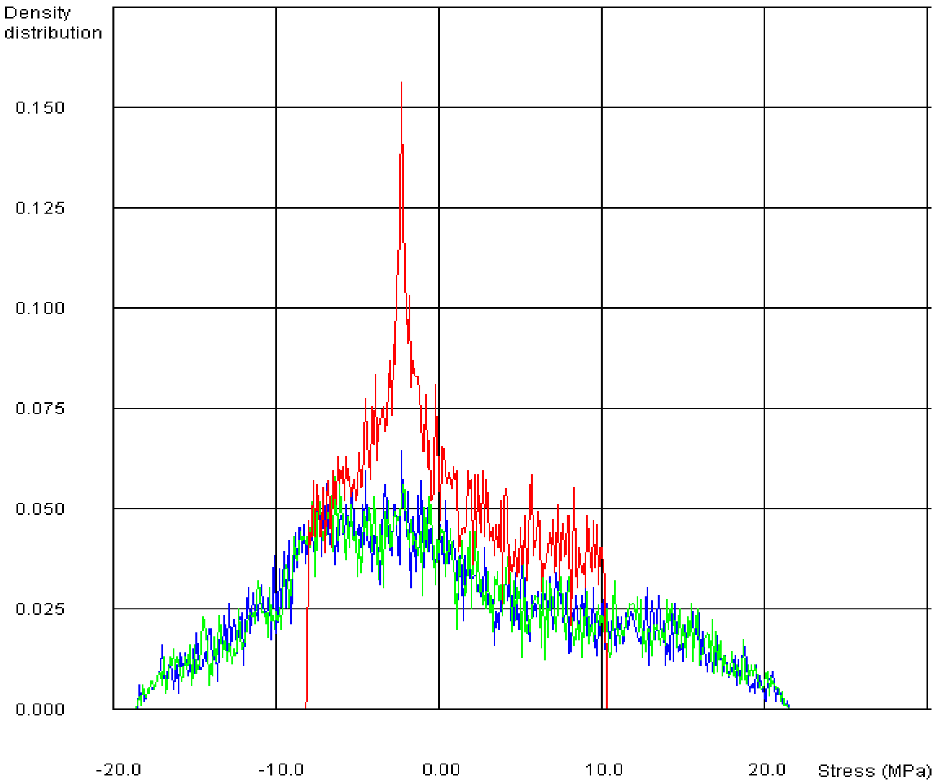

Figure 1. Probability distribution of normal stresses in grains under macroshear.

Application of the method to classical problem of homogenization gives new formulae for the effective moduli of disordered polycrystalline medium [3]. The effective moduli of multiphase polycrystal with grains moduli $C^{(\eta)}_{klmn}$ (v_η - is volume share of grains of η-th type) represented as

$$C^{*}_{ijmn} = \sum_{\eta=1}^{n} v_\eta \langle C^{(\eta)}_{ijkl}(\vec{r}_\eta)\left[I_{klmn} - A^{(\eta)}_{klmn}\right]^{-1}\rangle_\eta \ ,$$

which differs from Foight approximation of non-interacting grains by renormalization factors $A^{(\eta)}_{klmn}$. It resembles the situation in condensed matter physics, when the system of strongly interacting particles can be replaced by non-interacting quasiparticles but with renormalized masses [4].

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Researching damage mechanisms of carbon composites based on mechanical tests with monitoring acoustic emission

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To predict the behavior of a material during its use and for strength analysis of structures during mechanical tests, additional testing methods are applied, which allow to get more information about damage accumulation in the material. The acoustic emission method falls into this category of methods. Due to own specificity, acoustic emission monitoring makes quantitative assessment of fracture process possible in all volume of the material. Application of the acoustic emission method during mechanical tests of composite materials has been considered in [1, 2, 3, 4].

The mechanical tensile tests and the compression tests are carried out on the carbon composite material samples of 2 different grades by the Center of Experimental Mechanics equipment [5]. The electromechanical system Instron 5882 is used. The advanced non-contacting video extensometer (AVE) Instron is applied to measuring axial deformation of samples. During experiments the monitoring of acoustic emission is carried out in a continuous mode by an acoustic emission measurement system Vallen AMSY- 6. The maximum sensitivity of piezoelectric sensors is at frequencies from 450 to 1150 kHz. The peak amplitude and the energy parameters are selected as main parameters of the acoustic emission signals. The damage parameter is introduced by summation of energy parameter to analyze fracture kinetics. This parameter characterizes the degree of defect accumulation in the material [6]. Prior to testing, the synchronization of acoustic emission measurement system with the mechanical test machine and the advanced non-contacting video extensometer was done.

According to data from mechanical tests the deformation curves are constructed and mechanical characteristics of material, such as tensile strength, elastic limit, modulus of elasticity and maximum load, are determind. According to the damage accumulation curves, the analysis of the material's behavior during loading process is carried out. The main stages of the carbon composite fracture are determined based on parametric acoustic emission analysis. Depending on the material type the differences of fracture stages, and, as a consequence, differences of recorded acoustic emission signals are determined. The damage mechanisms are studied by comparing with the acoustic emission parameters.

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Simulation of damage during plastic metal deformation

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The phenomenon of fracture is widespread in nature and technology, and it has numerous causes and manifestations. Fracture is studied by different sciences having their own conceptual, experimental and theoretical bases. This paper deals with the mechanisms of damage and fracture of metallic materials under mechanical loads, namely, under plastic deformation.

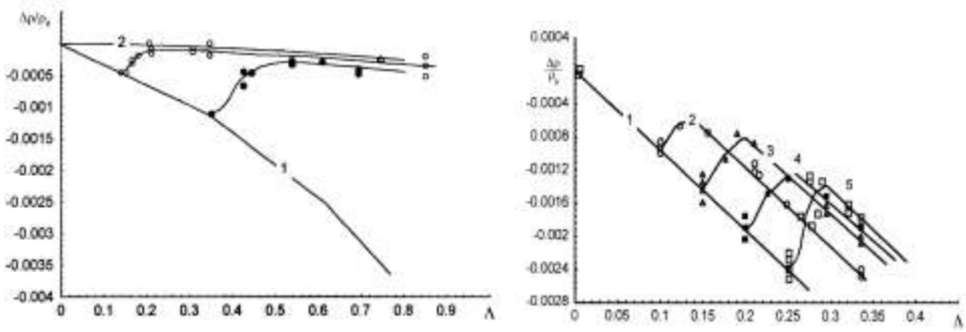
According to the current conception of metal physics, the fracture of metal materials is not a one-act catastrophic phenomenon, but a regular process of appearance and development of defects, which is in mechanics referred to as damage accumulation. Pure brittle damage is possible only in metals with a large covalent component in the interatomic bond. The form and shape of defects, as well as the velocity of their propagation, depend on metal behaviour and thermomechanical loading conditions; however, the active role of plastic deformation is invariant here, and it reveals itself on the macro- or microscale. This is why the deformational criteria of damage and the phenomenological theories based on a certain hypothesis of damage accumulation are widespread in mechanics and cyclic strength. In mechanics, the progress in the development of the notion of metal damage under plastic deformation is connected with the appearance of kinetic theories of dispersed fracture (damage mechanics). The process of damage under plastic deformation can be represented in a different way in terms of the dispersed fracture theory as kinetic equation (Kachanov and Rabotnov)

$$\frac{d\omega}{d\Lambda} = f\left(\omega, s_1, s_2, ...\right), \qquad (1)$$

where ω is a characteristic of metal damage; S_1 and S_2 are thermomechanical loading parameters depending on the loading conditions.

Note that in the literature there is no consensus on the form of the kinetic equation, and it is generally chosen by authors on the basis of hypothetical ideas or published fragments of metal-physic research data. The aim of this paper is to formulate a damage accumulation model proceeding from the analysis of experimental results on loosening of metal materials under deformation and to demonstrate its applicability to the prediction of fracture in plastic metal forming. The damage increment $d\omega$, as a scalar characteristic of material continuity, can be given a physical meaning of the plastic loosening increment. The experimental study of loosening was made on samples of aluminium, molybdenum, tungsten and steels of several grades. Four series of experiments were performed, namely: 1) tension of cylindrical and flat specimens, with the stress state remaining unchanged during deformation; 2) tension of cylindrical and flat specimens in two-stage deformation in a chamber filled with hydrostatically compressed liquid, the liquid pressure being different, though fixed at each stage of deformation in the range between 0.1 and 800 MPa; 3) tension of flat specimens, making specimens from them oriented at different angles to the initial direction of tension, further tension of the specimens; 4) tension of specimens, annealing and subsequent tension to fracture. At different stages of deformation portions of equal length were cut out of the specimens and subjected to triple hydrostatic weighing by the procedure for the determination of density, the relative change of which enabled one to judge about the damage accumulated.

Some results being shown in Fig. 1.



a b

Figure 1. Plastic loosening (relative change of density) during the tension of the samples of carbon steel 0.2%C: a -the tension has been carried out on the first stage under p = 0,1 MPa (line 1), on the second stage under p = 800 MPa (line 2); b - the tension of the flat samples of carbon steel 0.2%C oriented at angles 3π/8 to the initial direction of tension with shear strain Λ_0: 2 - 0.1; 3 – 0.15; 6 – 0.2; 5 – 0.25 (1 – without change of the initial direction).

The analysis of the whole collection of obtained data offers the damage model. When the stress state changes, the damage accumulated on the adaptation portion is evaluated as follows:

$$\Delta\omega_i = \left[1 + c_1\left(1 - e^{-c_2 \Delta k_i}\right)\left(1 - \frac{\lambda}{\lambda_a}\right)^{c_3}\right]\frac{\lambda}{\Lambda_f}, \qquad (2)$$

where Δk_i is the increment of the stress state index at i-stepwise of loading; $\lambda = 0 \ldots \lambda_a$ is a current amount of shear strain on the adaptation portion; λ_a is the length of the adaptation portion; c_1, c_2 and c_3 are empiric factors.

When the direction of deformation changes, the rate of damage accumulation decreases, and on the adaptation portion it can be determined by the formula

$$\Delta\omega_i = \left\{1 - c_4 |\vartheta_i| (1-\omega_{i-1})^{c_5} e^{-c_6(i-1)}\right\} \frac{\lambda}{\Lambda_{fi}}, \qquad (3)$$

where ϑ is the angle characterizing the change in the loading path in Ilyushin's phase space of deformations, which can be taken as a parameter for the quantitative evaluation of deformation non-monotonicity; ω_{i-1} is the damage on the portion preceding the *i*-th change in the direction of deformation; c_5, c_6 and c_7 are empiric factors; Λf is metal plasticity defined as limiting (at the instant of fracture) accumulated amount of shear strain Λ in deformation under constant stress state characterized by the stress state index k and the Lode-Nadai parameter.

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Analysis of plastic instability under dynamic loading conditions

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We have studied theoretically and experimentally the instability and localization of plastic deformation under dynamic loading and high velocity impact conditions

In the experiments, the behavior of samples was examined in a mode close to pure shear conditions using a Hopkinson-Kolsky bar to apply a dynamic load. The samples of a special shape and an appropriate test rig were developed to realize a plane strain state. The lateral surface of the samples was investigated in a real-time mode using a high-speed infra-red camera CEDIP Silver 450M with sensitivity ~25 mK (at 300K), spectral range 3-5 mkm, and maximum frame size 320x240 pixels. The temperature field distribution obtained at different moments of time allowed us to trace the evolution of plastic strain localization.

The study of the fracture surfaces of samples with a transmission electron microscope revealed that strip-like and honeycomb-like regions occurred in the areas of plastic strain localization

The process of perforation of a target involving plug formation and ejection was investigated using a high-speed infra-red camera. The ballistic set-up specially designed for studying perforation was used to test the samples in different impulse loading regimes followed by plastic flow instability and plug ejection. Changes in the velocity of a rear surface at different time of plug ejection were analyzed by means of Doppler interferometry techniques. The microstructure analysis of the recovered samples was performed using an optical interferometer-profilometer and a scanning electron microscope. Processing of 3D data obtained for the deformation relief at different time of plug ejection provided plastic strain gradient distribution estimates [1].

It is shown that the distribution of strain is relatively uniform in the initial penetration region with a smooth mirror-like fracture surface, whereas in the plug formation and ejection regions it becomes essentially non-uniform along the radius of a normal to the sample surface. Localization of plastic strain occurs in a thin region providing the plug formation. As the plug moves, the surface relief undergoes the roughening effect and the local inhomogeneities of shear deformation become larger.

In the strain localization areas, the subgrains are expanded into strips and then fragmented, forming an ultramicrocrystalline (UMC) structure with a grain size of about 300 nm. High angle misorientations of grains are due to rotational strain modes.

The appearance of plastic shear instability regions is simulated numerically. To this end, a theory developed in dearly works is used, in which the influence of microshears on the deformation behavior of the material is investigated by methods of statistical physics and thermodynamics of irreversible processes.

Theoretical and experimental results suggest that one of the mechanisms responsible for plastic shear instability and plastic strain localization under high-velocity impact conditions is related to structural-kinetic transitions in the microshear ensembles.

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Multiscale failure probability analysis in heterogeneous polydisperse composites

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The problem of determination of mechanical and physical properties of composites is highly topical. In some cases considerable efforts can be saved by replacing experimental testing with multi-scale simulations so that material properties are obtained by modelling at smaller scales [1].

One of the major barriers for applications of multi-scale methods is complexity of a micro-scale structure of composites. Such parameters as volume fraction of constituents, orientations, shapes, sizes and spatial distribution of inclusions significantly affect homogenized characteristics of heterogeneous materials. So, the urgent question nowadays is developing models capable to take into account the microstructural details of composites to calculate characteristics of deformation process for each phase of the material under different loading conditions.

The failure probability analysis is based on solution of micromechanical problems for characterization of nonlinear deformation processes. According to the stochastic approach, these processes can be described with multipoint statistical moments of stochastic stress and strain fields in microstructural components of a composite [2]. The first- and second-order moments (or average values and dispersions) are used for calculation of failure probability and for establishing links between fracture processes at microstructural and macroscopic scales. Using the concept of a Representative Volume Element (RVE), these moments were determined analytically using stochastic Boundary Element Method in elastic and elastoplastic cases, taking into account the statistical properties of the structure and loading conditions.

A class of heterogeneous materials with randomly distributions of spherical inclusions in matrix has been considered in this work. Statistical information about geometry of such materials at a microscopic scale can be characterized with high-order multipoint correlation functions [1, 3]. In the suggested new mathematical models the correlation functions up to the fifth order are used, which will allow more accurate description of details of heterogeneous microstructure of composites.

New numerical results were obtained for characteristics of micro- and macro-scale stress and strain fields as well as for parameters of deformation and failure process for several types of randomly reinforced heterogeneous materials under different loading conditions. The effects of microstructure geometry and physical parameters of components on parameters of damage process have been studied.

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Two-scale models of polycrystals: issue of macroscale motion decomposition, loading process image and check postulate of isotropy by Ilyushin

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Requirement for production of structural materials with prefixed behavior exists at present. But nowadays obtaining such materials requires extensive full-scale and expensive experimental research. Modeling of inelastic behavior of the metals and carrying out numerical experiments allow to reduce these costs and to extend range of application. The paper considers the application of multiscale mathematical models of crystal plasticity [1] to description of severe inelastic deformation of single- and polycrystals for which geometric and physically nonlinear constitutive relations are required.

One of the unsolved problems in nonlinear solid mechanics (and in construction of multiscale models in particular) is how to single out the component of material motion responsible for geometric nonlinearity (for example, when rigid rotations are imposed on strain-induced motion) or, in other words, how to decompose the macroscale motion into quasirigid motion and strain-induced motion [2]. We consider three possible methods of representing the quasirigid motion on the macroscale [3, 4]. The motion of rigid coordinate systems descriptive of quasirigid motion is defined by a specific hypothesis of decomposition of the motion on the macroscale. The hypotheses under consideration are the following: (i) the whole motion of the representative volume is strain-induced motion; (ii) the motion is decomposed into strain-induced motion and quasirigid motion whose spin is determined by averaging mesoscale spins calculated from a certain general lattice rotation model; and (iii) the quasirigid and strain-induced motions are defined respectively by the antisymmetric and symmetric parts of the macroscale displacement velocity gradient.

For each method, consistency conditions [3] are determined; from these conditions also follows a relation between macroscale quasirigid rotation and mesoscale rotation of elements. It is shown that determination of rotations on the scales “from the top down” makes it impossible to select an arbitrary rotation model on the lower scales, and this considerably limits the applicability of physically substantiated rotation models on the lower scales [5]. It is shown that the proposed method of defining the macroscale quasirigid motion as an averaged mesoscale spin makes it possible to obtain consistent constitutive relations of neighbor scales with no limitations on the choice of a lower scale rotation model. It is shown that with the first hypothesis, the loading process image depends on the rigid motion imposed on the representative volume as a whole; with the other two hypotheses, the process image does not depend on the choice of a reference frame. At the same time, the third hypothesis makes it impossible to determine the lattice rotations independently of macroscale kinematic relations which, in fact, are determined by micro- and mesoscale physical interactions.

Also in this work the issue of application multiscale models inelastic deformation mono- and polycrystals of crystal plasticity for check postulate of isotropy by Ilyushin in case of large strains is considered. Specifically, different approaches a macrolevel decomposition of movement towards a rigid rotation (is describing of movement a rigid moving system of coordinate (MSC)) and deformative displacement (respect to MSC). Definition of strain path in terms of MSC is introduced. Applicable kinematic influence in terms of laboratory system of coordinate is obtained. The result of numerical experiments allow to conclude, that an accuracy of compliance of postulate of isotropy by Ilyushin [6] depend on decomposition of the motion on the macroscale, particularly postulate is more accurately in case hypnotize (ii), than in case hypnotize (iii).

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Fragmentation of the zirconia ceramics with different porosity under dynamic loading

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An extensive experimental investigation on zirconia ceramic specimens with different porosity was carried out to evaluate the influence of porosity on fractoluminescence pulse distribution and energy dissipation. Experiments were carried out using Split Hopkinson Pressure Bar (SPHB) setup with strain rate from 500 to 5000 s-1. Porosity of the specimens was varied from 10% to 60% volume fraction. Energy dissipation was calculated from the SPHB data. Acoustic emission is widely used to detect and investigate multiple fracture processes of rocks and concrete. But due to high strain rate it is impossible to use it on the dynamic fragmentation. It was found that the fractoluminescence [1] (light emission due to fracture) can provide valuable information about evolution of fragmentation at high strain rates [2]. Despite that the zirconia is not as transparent as fused quartz it was possible to detect fractoluminescence from the surface and sub-surface layers of the specimen. Fractoluminescence was detected by a fast PMT. Signal from the PMT was recorded by oscilloscope with 1 GHz sample rate. Record length was 100M points which is equal to 0.1 s. Analysis of the fragment size distribution shows that it can be approximated by power law where power (slope in log-log coordinates) depends on the porosity.

Fractoluminescence consists of pulses with sharp front and exponential decay with different amplitudes. Pulses were recorded even 10 ms after the loading pulse whit is order of magnitude higher than load pulse duration. Amplitude of the pulse depends on energy released during single fracture event and position of the fracture (depth and orientation to the PMT) which makes hard to measure energy release alone. We decided to measure intervals between subsequent pulses (or the rate of the pulses as in the Omori law). It was found, that interval complementary cumulative distribution is bimodal power law distribution. Knee position depends on the porosity of the specimen

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Porous copper and silicon under shock-type loading

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Porous materials are investigated in strengthening and dislocation dynamics aspect. For that custom atom configurations are fabricated with own custom software. Atom configurations used in LAMMPS molecular dynamics simulation machine. Basic Stillinger-Weber and EAM type potentials used in silicon and copper simulations. Silicon got the eye of researcher after a brief experience with tetrahedral liquids as having the most tetrahedrality ratio amongst tetrahedral materials. For copper prepared sample is a cube with side of 46 nm. Porosity volumetric ratio values in 10-30% range. After fabrication, sample is treated with shock-type stressing which leads to creation of dislocations. Time periods of slope in shock stressing are about 10 ps. Pressure at pitch point is 100 kbar. After shock treatment, modified sample is compared to clean lattice sample via loading with adiabatic linear extraction in time. Response of samples is presented in pressure computed, typical material response is shown in Fig. 1. Also internal structure of samples is controlled through all computations, picture produced with custom software is shown at Fig. 2.

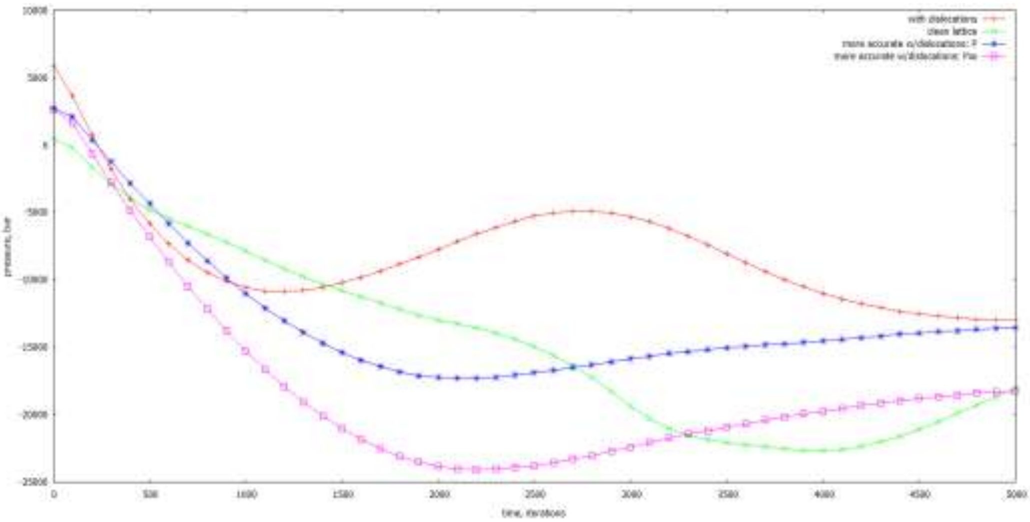

Figure 1. Preliminary reseach results. Dynamic response of copper on linear adiabatic extraction after preliminary processing with shock-type stressing and without such. Notice the difference between clean lattice response (green) and lattice with dislocations (red).

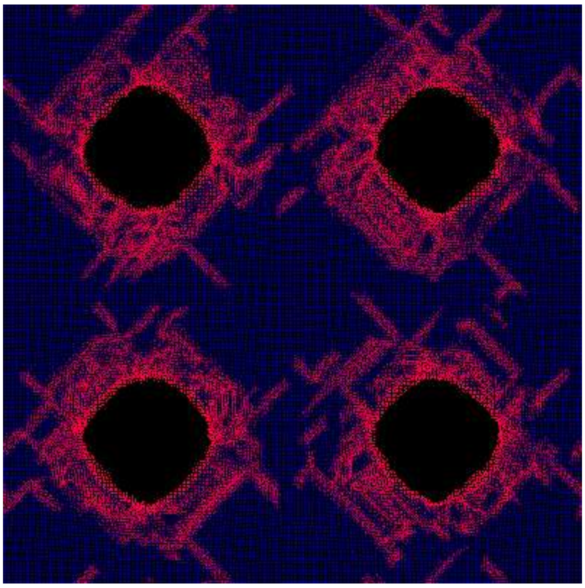

Figure 2. View of prepared sample with dislocations (cube is sliced at z=0.25). Original lattice was oriented along sides. Pores were created equidistantly in lattice-like positions.

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Structure, phase formation and mechanical behavior of aluminum composites after shock-wave loading

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The present paper uses shock-wave (SW) loading of Al nanoparticles to create light nanocomposite with increased physico-mechanical properties. Russian civil explosive Uglenit was chosen as high energy material for compacting. The formation of the structure and properties of aluminum based materials after shock-wave loading was studied. It was found that SW treatment of different samples a) aluminum powder, b) powder mixtures Al +10 wt.% C (in the form of detonation nanodiamonds) and c) Al +10 wt.% Al_2O_3 produces nanostructed materials with almost the theoretical density.

X-ray diffraction analysis showed that in the samples with the addition of carbon and aluminum oxide was formed two-phase state of aluminum with a significantly different structure parameters (Fig.1). This state is indicated with an arrow on Fig. 1 - a small reflection near the main one, which belongs to aluminum.

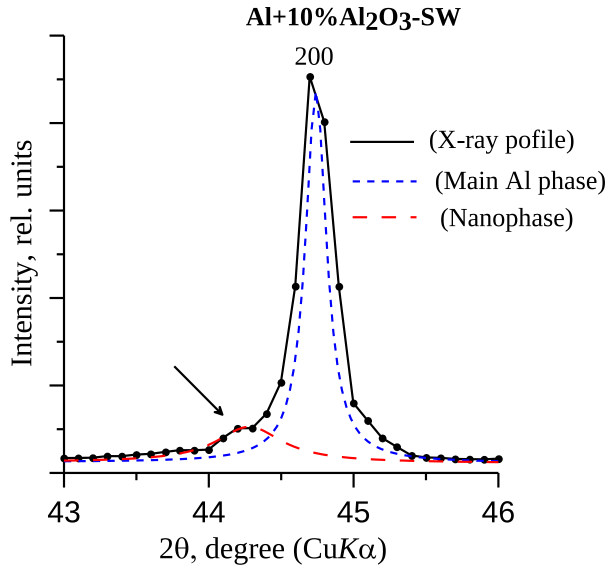

Figure 1. X-ray spectra of the Al–Al_2O_3 sample obtained by shock-wave loading.

In this case, the lattice parameter of nanophase increased by 0.5%, which testifies to its non-equilibrium state. This increase of the parameter may be due to compressive stress, evaluation of which gives the value of 350 MPa. The fact that there are many residual stresses influences on mechanical properties of SW-treated materials. Indeed, hardness measurements have indicated a 10-time increasing with maximum values for samples containing aluminum oxide, which is likely to be due to transformation of part of the bulk of the material to a nanocrystalline state, with the characteristic size of the structure elements being 10 nm. Furthermore, the yield strength and the value of strain to elastic limit of the materials obtained by SW-loading significant increases. It was shown that the materials have high values of mechanical properties - hardness, compressive yield strength (Table 1).

Table 1. Mechanical characteristics of samples

Sample	Hardness, HV, MPa	Yield strength, MPa	Strain to elastic limit, ε_y
Al technical grade	190	30	0.0036
Al after SW- loading	870	-	-
Al+C after SW-loading	1025	400	0.023
Al+Al_2O_3 after SW-loading	1360	500	0.0205

It was been shown that the microdistortion of aluminum crystal lattice has increased after adding hard particles. In this case it possible to estimate reserved energy. This energy increases when high-modulus particles are added. Apparently a shock wave taking place in powder containing tube seems to spend its energy on Al activation as well as on activation of particles.

Assuming the simplest case of additive contribution to activation of Al particles by hard ones estimates of reserved energy of alumina and nanodiamonds can be obtained. The value for alumina comprised 1.1 J/kg and for nanodiamonds, the value was two times lower. This can be explained by complexity of phase composition of carbon mixture consisting of an X-ray amorphous phase, diamond phase and crystalline carbon.

Development of the system for measurement of length and monitoring of evolution fatigue crack

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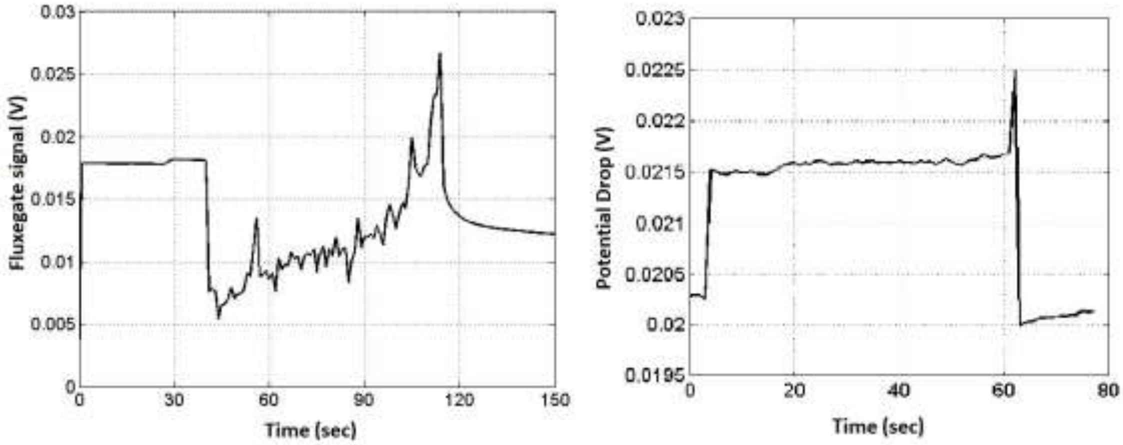
Today we need to ensure the safe operation of the resource mechanisms and structures for high production efficiency. Such as bridges, railways, parts of cars and planes. Sometimes secure the operation of the objects reached at least 10^{10} cycles. To research a material during 10^{10} cycles it is required a lot of time. Ultrasonic test machine is used for getting the results during the short period of time [1-3]. The main effect which is character for the material behavior testing in the gigacycled fatigue is subsurface fatigue crack initiation. The analysis of published investigations let us to understand that the physical mechanisms underlying these effects are unexplained today. At present there are several models of the phenomenon, such as the model proposed in [4-6].

Fatigue tests were carried out on the ultrasonic testing machine USF-2000, manufactured by Shimadzu. Samples were cooled by air flow during test. The experiment was finished when change of the resonant frequency of the specimen reached the 10 %. There are two methods to study of a crack length. The first method is based on the effect of magnetic permeability change of the sample during the defects initiation. The developed experimental setup is a modification of fluxgate method. In this case, the sample is the object of study and the fluxgate detector simultaneously. The second method is based on the monitoring of electrical resistance changes of the sample. There are two couples of the contacts on a sample. Electric current flows through the couple of the external contacts. Voltage drop is detected by the second couple on the contacts.

Several tests were carried out on the base of two methods described above. As a result the time dependence of the signal from the fluxgate detector and the time dependence of the potential drop from the sample are presented in figure 1. At the final stage of the experiment both methods illustrate jumpwise increasing of the data that indicates the moment of the beginning of the defect initiation process. Thus the development of presented techniques will allow us to detect structural defects inside of materials in situ. As a results of the experiments, it was shown that the significant change of the physical processes accompanying the evolution of structural defects in the material was observed on the final stages of the experiment. The obtained data allowed us to estimate the characteristic time of the sub-surface fatigue cracks evolution that cannot be monitored by the standard non-destructive methods.



A B

Figure 1. The time dependence of the signal from the fluxgate detector (A) and the time dependence of the potential drop from the sample (B).

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Hugoniot elastic limit and spallation strength of cubic boron nitride polycrystalline samples

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The elastic limit and the spallation strength of a superhard cubic boron nitride modification (c-BN), hardest material after diamond [1], were investigated under shock-wave loading.

Polycrystalline c-BN samples were prepared by pressing of fine-dyspersated boron nitride powder in the high pressure chamber at 7-8 GPa, 1700-1800 C and time of the process of 2 minutes. The samples were of high quality, their porosity was less than 1%. The diameter and the thickness of the samples amounted to 12,7 and 2,1 mm consequently.

Shock-wave loading of the samples was carried out using Al impactors, accelerated by explosion products up to 5 km/s. Sample surface velocity registration was conducted by laser Doppler interferometer VISAR of high spatial and time resolution.

Two-wave configuration with the formation of elastic and plastic waves has been observed. The amplitude of the elastic precursor determined from registered particle velocity profiles was found to be 55±1 GPa, which corresponds to Hugoniot elastic limit (HEL) of 35±0.5 GPa. The estimation which was made using the data from [2] allows affirming that HEL of c-BN polycrystalline samples is comparable to that of diamond crystal. The spallation strength of the samples was investigated at loading pressures both lower and higher than the pressure of onset of plastic deformation. It was found that in the elastic region the spallation strength is much smaller than HEL and changes from 0.7 to 1.6 GPa, which is probably caused by fragile destruction of the heterogeneous material. In the elastic-plastic region the spallation strength increases to 2.4 - 3.2 GPa, which can be explained by the deformation hardening.

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Nonlocal conditions for the transition damage to a localized failure in rocks and granular composites under quasistatic triaxial proportional and non-proportional loading

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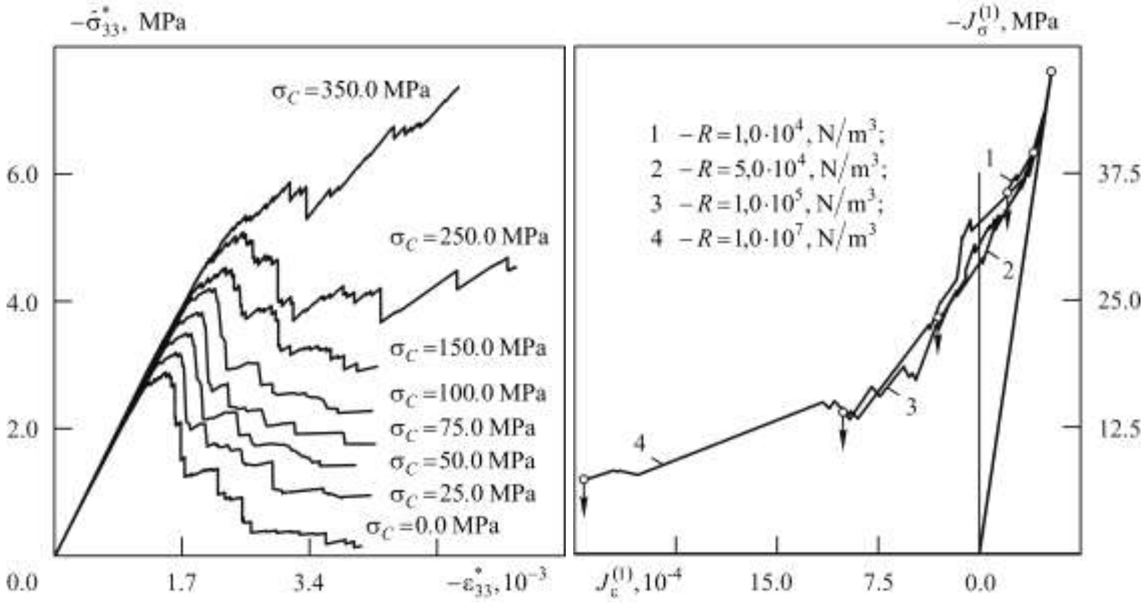
The investigation of inelastic deformation and failure of rocks and granular composites is associated with the necessity to develop mechanical models for the correct description of the behaviour of damaged heterogeneous materials in elements of structure. Besides, there is a need to improve the procedures of strength analysis in order to take into account actual loading conditions and the evolution and character of the collective interaction in a system of defects which determines the instant of macrofailure, when the damage accumulation becomes unstable. Without understanding the regularities and mechanisms of damage accumulation, without evaluating its stability and determining the conditions of localization begining, the macrofracture of composites will remain latent and poorly predictable phenomenon of internal structure evolution of the material.



A B

Fig. 1. Stress-strain diagrams for rock media under uniaxial compression with different lateral pressure σ_C (A) and dilatation phenomena under uniaxial compression with different stiffness of the loading system R (B).

The two-level-phenomenological structural model of rocks media and granular composites was developed with the aim to study the character of collective multi-particle interaction in the defect ensemble, the general laws and the change in failure mechanisms and scale levels of damage evolution under combined triaxial quasistatic proportional and non-proportional loading [1–3]. A partial or complete loss of load-carrying capacity by structure elements is connected with violation of strength conditions and, as consequence, with jump-like changes of deformational characteristics. The model allowed us to describe the inelastic deformation accompanied by inclination and coarsening of defects as a multistage process of damage accumulation and to determine the instant of composite macrofailure as a result of loss of stability of this process.

In the course of computational experiments, we found and analyzed such regularities of mechanical behaviour of rocks media and granular composites as the strains corresponding to the instant of macrofailure and the character of damage evolution in relation to the stiffness of the loading system [1], the unequal resistance of heterogeneous bodies [2], the effect of lateral pressure on strain-softening (Fig. 1, a) [2], the dilatation under uniaxial compression (Fig. 1, b) [2], and the self-supported accumulation of defects [4].

A nonlocal critical dimensional lengths constant for damaged solids is found to exist, which does not depend on the type of stress-strain state and quasistatic proportional and nonproportional loading modes [2, 5, 6]. The constant determines the instant of transition from the stage of accumulation of disperse damage to a localized failure and to the strain-softening. The new nonlocal criterion allow one to determine a unique quantitative relation between the connection of damaged domains and the regularities in the behaviour of isotropic and anisotropic media [7].

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Deformation and fracture behavior of human dentin at low temperature

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Human dentin is a natural multilevel composite that consists of an apatite mineral phase (approximately 50% by volume), collagen fibers (approximately 30% by volume) and 20% of water. Therefore, stress accommodation mechanisms of dentin should include the contributions of both inorganic and organic phases. Deformation and fracture behavior of dentin could vary from elastic-plastic to almost undeformable in dependence of geometry stresses applied to the sample. Mechanical properties of an organic substance dramatically depend on temperature. For example, some organic materials become brittle when they are dipped in liquid nitrogen. Hence, mechanical testing of dentin in liquid nitrogen should exclude the plastic response of the collagen fibers from its deformation behavior. Comparison of deformation behavior of human dentin under compression at 77K and 300K has shown that it is similar, but the values of mechanical characteristics depend on the temperature. Compression strength and elastic deformation of dentin at 77K is higher than at room temperature and its plasticity is lower. The total plasticity of dentin is the sum of contributions of both collagen fibers and geometry of sample at room temperature. Collagen fibers do the sole contribution into plasticity of the high samples, where tensile stress level is high. On the contrary, the geometrical factor is the dominant for the plane. Diametral compression testing is experimental technique applied to both brittle materials and small-sized samples, which is alternative to tensile test. At 77K dentin behaves like almost brittle material under such deformation scheme: it is deformed exclusively in elastic regime and it fails due to the growth of the sole crack. On the contrary, dentin demonstrates ductile response at 300K. There are both elastic and plastic contributions in the deformation of dentin samples. Multiple cracking and crack tip blunting precede the failure of samples under diametral compression. Organic phase play the important role in the fracture mechanism of dentin: plasticity of the collagen fibers could inhibit the crack growth.

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Zirconia – alumina porous ceramic produced by using aluminum hydroxide

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Recent developments in science and technology have heightened the need for porous ceramic as an advanced material. However, there is increasing concern that using porous agents for porous structure formation as the most efficient method leads to the contamination of the structure with carbon and its compounds. The alternative approach is to use hydroxide compounds decomposition. In present study to synthesized porous ceramics aluminum hydroxide was used. The influence of granulometric and phase composition of zirconia and aluminum hydroxide powders on the structure and properties of ceramic composites ZrO_2 - Al_2O_3 was studied. Data analysis showed that the content of tetragonal zirconia in porous ceramics ZrO_2 - Al_2O_3 was determined by two factors: the presence of alumina oxide suppressing ZrO_2 grain growth for critical grain size in zirconia not to be achieved and porosity, which reduced the critical grain size of tetragonal ZrO_2 due to the increasing number of grain contacts. The crystallite size of tetragonal zirconia by which non-porous state of sintered ceramics ZrO_2 - Al_2O_3 is achieved was estimated by extrapolation method.

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Investigation of anomalous compressibility of cerium and docosane under shock-wave action

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The paper is dedicated to the study of shock-wave properties of substances in the anomalous compressibility region. Cerium and docosane (saturated hydrocarbon $C_{22}H_{46}$) were selected as the objects of the investigation. Anomalous compressibility of cerium has been studied earlier [1,2], but such unusual behavior of docosane was first discovered by the authors.

Cerium has a certain number of unusual properties as compared to most metals. These include the existence of a critical point in the solid state on the line γ-α phase transition, significant, about 13-16% abrupt change in the specific volume at the phase transition and the anomalous compressibility γ-phase. This makes cerium important material for researches aimed to obtaining its multiphase equation of state of the material and its strength properties. In shock-wave experiments the uniaxial deformation is realized and that leads to shear stresses in the elastic-plastic medium.
In this paper we determine the shear stress and evolution of compression wave in the area of cerium anomalous compressibility. The value of longitudinal stress at which the γ-α phase transition occurs is also determined. It is shown that the phase transition pressure, calculated on the basis of shear stress, under dynamic and static compression coincide and is equal to 0.8 GPa.

The dependence of spall strength of cerium on the strain rate is investigated. At its increase by an order of magnitude (from $1.5\cdot10^4$ to $8.5\cdot10^5$ s^{-1}) the spall strength rises from 0.3 to 0.8 GPa.
Similar experiments with docosane in solid and liquid state have been conducted. It was shown that the solid docosane demonstrate an elastic-plastic properties and has abnormal compressibility at pressures below 100 MPa. It was found that the strength of docosane remains practically constant and equals to about 24 MPa when passing through the melting point.

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