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Perm State Technical Research University (Perm, Russia)
Georgia Institute of Technology (Atlanta, USA)
Arts et Metiers ParisTech, LAMEFIP(Bordeaux, France)
Perm Region Government (Perm, Russia)

International Workshop

"Advanced Problems of Mechanics and Physics of Mesoscopic Systems"

February 1-4, 2011, Perm, Russia

Book of abstracts

Perm, 2011

The subject is focused on multiscale phenomena, related to the collective behavior of mesodefects ensemble, problems of damage localization, damage-failure transition, scaling laws of crack nucleation and propagation under high cycle, ultra-high cycle fatigue, dynamic crack propagation, scaling phenomena in seismic events. The goal of the Workshop is the joining of efforts of researchers working in the area of scaling analysis of structure characterization using high resolution 3D set-ups, to establish the linkage of multiscale spatial-temporal invariants, the effect of materials defects in crack initiation, scaling laws of damage-failure transitions, the data of advanced experimental methods for the constitutive modeling describing the spatial-temporal universality of characteristic stages of damage-failure transitions.

Main topics:

- Advanced methods for 3D analysis of defect induced multiscale structure evolution.
- Scaling analysis of damage-failure transition related to the study of fracture surface and surface morphology, acoustic emission and seismic data.
- Role of spatial-temporal invariants of structure evolution in constitutive modeling.

ISBN ___________

Institute of Continuous Media Mechanics of Russian Academy of Sciences (Perm, Russia), 2011

Contents

SPECIAL FEATURES OF THE DEFORMATION LOCALIZATION DEVELOPMENT AT THE MESOLEVEL WITHIN A MICROPOLAR MODEL OF ELASTOPLASTIC FLOW

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It is experimentally stated that along with translational modes of deformation rotational ones develop in polycrystals. Separate grains, their fragments and grain conglomerates experience rotation. Internal rotations are mainly caused by the lack of active slip systems and defect flow interaction at interfaces of mesostructure fragments. The insufficient shear accommodation in a conjugate slip system under constrained deformation induces the torsional moment formation. At the macrolevel the influence of internal moments that effect essentially the structure fragment behavior at the mesolevel is averaged and vanishes. Based on this physical prerequisite, the proposed model describes the behavior of meso- and microstructural elements from underlying scale levels using an additional degree of freedom, i.e., independent rotations. Shear deformation and stresses as well as bending-torsion and couple stresses develop in the medium. It is also important to note that in most cases such models stay within the elasticity stage. In the proposed paper the Cosserat model is applied to a plastic flow region.

In the paper we analyze flow curves and evaluate the couple stress contribution to the deformation response of the material. The energy distribution between stresses and couple stresses leads to an increase in couple stress contribution and consequently to a decrease in stress contribution with strain. The stage character of flow curves can be related to the development of independent rotations in the medium and growth in couple stresses.

The two-dimensional calculations of elastoplastic deformation for homogeneous specimens and polycrystal mesovolumes allow concluding on the effect of independent rotations on the development of localized bands of plastic deformation. Plastic strain decreases in bands, i.e., the consideration for rotations leads to the same effect as strain hardening.

MECHANISMS OF DEFORMATION AND FRACTURE IN COATED MATERIALS AT THE MESOSCALE LEVEL. MULTISCALE NUMERICAL SIMULATION

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The deformation and fracture of composite materials with coatings are simulated. A dynamic boundary-value problem in a plane strain formulation is solved numerically by the finite-difference method. The mechanical response of a steel substrate and a boride coating is described by respective models for an elastic-plastic medium subjected to isotropic hardening and for elastic-brittle fracture. To simulate the mechanical response of the steel substrate use was made of the relaxation constitutive equation based on microscopic dislocation mechanisms. An introduction of a mesovolume with a boride hardened layer of a complicated geometry in an explicit form (fig.1) allows us to prescribe the length scales – scale hierarchy of inhomogeneities, whose characteristic sizes might differ by two orders of magnitude. A series of numerical experiments was conducted for varying strain rate of tension and compression.

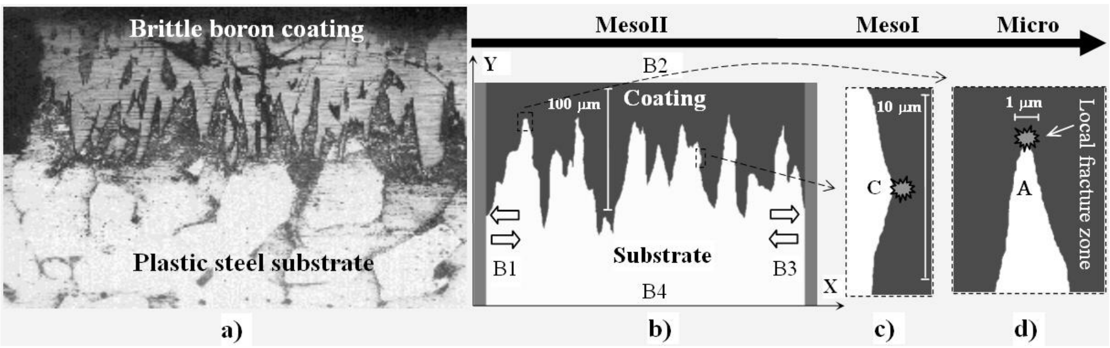

Fig.1: Mesovolume of the composite and characteristic sizes of inhomogeneities at different scale levels: *(a)* experiment and (*b*–*d*) simulation.

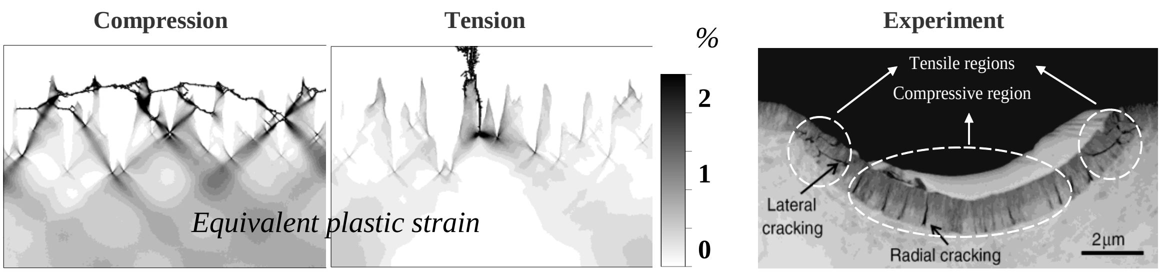

Fig. 2: Different directions of crack propagation under tension and compression in comparison with experimental patterns after microindentation of a coated steel (Tilbrook et al., Acta Materialia, 2007).

Macroscopic behavior of the composite is shown to be controlled by interrelated processes of localized plastic flow in the substrate and cracking of the coating.

The following conclusions can be made.

1. The local regions of bulk tension are shown to arise near the interfaces even under simple uniaxial compression of the composites that controls the mechanisms of fracture at the mesoscale. Both for external tensile loading and external compression of the composite material, cracks in the coating tend to originate predominantly in the regions of local tension and propagate under tensile loads in different directions (Fig. 2).
2. The macroscopic strength under tension changes but only slightly with the strain rate increasing, while under compression it increases. The higher is the compression rate, the less intensive is the fracture of the coating.
3. The macroscopic stress depends exponentially on the compression strain rate. This dependence hardly changes with the plastic strain development.

Acknowledgements. The work is supported by DFG (SCHM 746/84-1, SCHM 746/103-1) and by the President of Russian Federation through the grant MD-6370.2010.1.

FATIGUE RESISTANCE AND MICROSTRUCTURE SCALING PROPERTIES OF PRE-STRAINED ALUMINIUM ALLOYS

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Research topic of advanced materials used in aircraft and machinery to ensure long service life, never lose their actuality. In particular, growth of interest to research of influence preliminary loading (quasistatic, dynamic) on characteristics of fatigue durability for a wide class of materials is observed. Low cycle fatigue and quasi-static and dynamic pre-loadings can represent foreign object damage for the application in the aircraft engine industry. The objective of this work is to provide the link between the fatigue behavior of pre-strained aluminium alloys and the scaling properties of damage induced on the fracture surface. Two aluminum alloys Al-Cu and Al-Mg were investigated in the preloading conditions. Loading of samples was carried out by two ways - quasistatic and dynamic stretching then samples were exposed to the cyclic loading corresponding to base service life (approximately $2*10^5$ cycles). The investigated materials have various sensitivity to preliminary loading. It was experimentally shown, that fatigue resistance of alloy Al-Mg reveals weak sensitivity on preliminary loading, at the same time for alloy Al-Cu fatigue resistance sharply decreases.

Comparison of scaling data (in terms of the Hurst exponent) for the samples which reveal high and low sensitivity of mechanical characteristics to preliminary loading, allows the following conclusions:

- Two mentioned alloys have qualitative different fatigue responses to quasi-static and dynamic preloading, that reflects distinct sensitivity to high cycle fatigue resistance relative to possible foreign object damage.
- Low sensitivity of Al-Mg alloy to preliminary loading is caused by high degree of dissipation channels of a material to various modes preliminary loading - initiation of mechanisms of a structural relaxation at various scale levels. It proves to be the reason of a considerable variation of the Hurst exponent - scale invariant, reflecting correlation mechanisms of a structural relaxation at various scale levels.
- The morphology of fracture surfaces for Al-Cu alloy revealed the scaling universality in term of the Hurst exponent. The Hurst exponent reflects the self-similar scenario of damage kinetics related to long-range correlation properties of defects providing damage-failure transition under HCF crack propagation.

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LOCALIZATION OF PLASTIC DEFORMATION IN METALS WITH INTERSTITIAL ATOMS

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Austenitic stainless steels are a priority class of construction materials. It is common knowledge to date that introduction of N, C and H into γ-Fe causes a significant enhancement of the yield limit, $\sigma_{0.2}$, and the work hardening coefficient, θ. The macrolocalization behavior of plastic flow has been investigated in sufficient detail and the observed types of localization patterns have been related to the respective stages of the loading curves obtained for these materials.

New experimental evidence has been obtained, which suggests that the evolutionary behavior of plastic deformation localization is affected by the interstitial impurity content. The investigations were performed for FCC monocrystals of the following steels: Fe-18%Cr-12%Ni containing 0%, 0.35% and 0.5% nitrogen and Fe-13%Mn containing 0.93% and 1.03% carbon. Hydrogen was introduced in the studied specimens electrochemically under controlled cathodic overpotential of 100 mV from 1N H_2SO_4 solution with addition of 20 mg/l of thiourea as a hydrogen poison. Electrochemical cell with calomel reference and platinum counter electrodes was de-aerated and kept under N_2-gas bubbling and 50 ^oC during the whole charging process of 70 h for all specimens. Current density at the applied potential was less than a few mA/cm^2 during the whole charging process for both materials. No hydride or any other phases were detected with X-ray diffraction method in the specimens after applied hydrogen charging.

Variation in the impurity content and extension axis orientation of the test specimens is found to cause a changeover in the shear process type (single/multiple slip) and the deformation mechanism involved (dislocation glide/twinning).

The single crystals were prepared and tested in tension on an Instron-1185 testing machine. Using the method of speckle photography, displacement vector fields, $\boldsymbol{r}(x,y)$, were recorded simultaneously for individual points on the specimen gauge part. The tests were carried on at room temperature for the stainless steel γ-Fe_I monocrystals containing nitrogen solid solution and for Hadfield steel γ-Fe_{II} monocrystals containing carbon solid solution. Matching of the results obtained for the above two sets of specimens reveals that in the latter case, the values $\sigma_{0.2}$ and θ change less significantly with growing interstitial impurity content. The examination of local elongation distributions over the specimen extension axis, $\varepsilon_{xx} = du/dx$ (u is a component of the displacement vector $\boldsymbol{r}(x,y)$ in the direction of extension axis x)

has shown that at the linear work hardening stage in the deforming specimen there occurs a wave process, which is characterized by propagation rate, V_{aw}, and wavelength, λ.

It has been found that the propagation velocity of the localized plasticity waves, $V_{aw} \approx 10^{-5}$ m/s. At the linear work hardening stage this value is inversely proportional to the work hardening coefficient and is determined by the interstitial impurity content. The wavelength of plastic deformation localization is inversely proportional to the plastic flow stress averaged over the linear work hardening stage.

Thus, the above experimental evidence strongly suggests that the plastic deformation localization parameters (V_{aw} andλ) are affected by the strength characteristics of steels, which are determined by the interstitial impurity content (C, N, 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.

FUNDAMENTAL FOR ELECTROMAGNETIC PULSES AND WEAK VIBRATIONS INFLUENCE OVER DESTRUCTION PROCESS IN TERRESTRIAL MEDIUM /Similarity and specific features of full-scale and laboratory effects, models of mechanisms/

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The presentation involves several topical parts, united by relevance to problem of induced seismicity and possible application of physical fields to reduce the tectonic overstress in order to decrease strong earthquake hazard. The first part includes a review of peculiar features of approach and models to understand the mechanism of seismicity triggering, which means external influence on fracturing in a terrestrial crust. Structural heterogeneity of the Earth's crust (geological medium) on different scales was previously considered as a circumstance that complicated the description of its stress-strained state and limited the opportunity to use the approaches of Continuum Mechanics for earthquake prediction. As a new area of geomechanics and seismology develops (i.e. artificial relaxation of excess stresses in geological medium), we can see that it is structural heterogeneity that creates prerequisites for realization of triggering effects (responses of dynamical events, particularly seismic activity, on action of relatively weak factors). Indeed, because of structural heterogeneity at any stage of geological medium destruction there are zones of inelastic (pseudoplastic) strain which are much more susceptible to influx of energy from outside. Observations of induced and man-made seismicity may be indicative of possibility (on special conditions) of controlled influence on seismicity with the purpose of initiating weak events and increment of energy released by those events. The experimental electromagnetic soundings performed on the territory of Bishkek geodynamic test site (Northern Tien Shan) with high-current source of electrosounding - electric sounding generator unit (ESGU) may be considered as one of such episodes of "artificial" influence. In order to confirm this we analyzed the data of KNET telemetric network which involves 10 digital seismic stations. Statistically significant correlations between changes in weak seismicity and electric transfer during electromagnetic soundings were revealed (using superposition technique for observation periods). The obtained results are in agreement with previously published materials about influence of discharges during runs of geophysical MHD-generators on spatio-temporal redistribution of seismicity.

The second part is devoted to laboratory modeling. In the experiments with loaded rocks specimens we recorded variations of acoustic emission, AE, of different rocks (granite, gabbro, marble, rock salt) under action of EM field. The experiments have been conducted on noiseless rheological presses of maximum compression load of 100 tons. The session with additional electric supply took place during specimens creep tests. It is important that the strength of applied electric field of was 1-10 kV/m, i.e. much less than that in the case of well known electroplastic effects in ionic crystals. The effect of short-term increase of AE activity stimulated by external impacts on semi-brittle and pseudoplastic materials under conditions of uniaxial compression has been revealed. We studied the peculiarities of AE responses similar to memory effects (delay, aftereffect, degradation of response to repeated impacts). We determined the range of values of compressive stresses in which there is an effect of short-term AE activation (not related to a macrocrack formation in a sample and chips on its lateral surfaces. It is shown that under a load which is 70-95 % of maximal value (for a given sample), solitary responses do not lead to change in deformation, more than 10^{-5} (i.e. correspondent changes of specimen sizes are less than micron).

The last part is dedicated to mechanisms of (theoretical approach). A new model has been proposed for the effect of electrical pulses on cracking rate in loaded terrestrial materials with primary low frequency vibrations excited by nonlinear resonant electromagnetic interactions similar to stimulated Brillouin scattering. The model explained the nontrivial similarity between the responses of specimens with greatly differing properties.

FRACTAL CHARACTER OF GLASS FRAGMENTATION

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Comparative analysis of fragmentation statistics was carried out for quasi-static and dynamic loading of glass samples. Quasi-static testing was performed in experiments with glass plates loaded in a "sandwich" to save glass fragmentation pictures [1]. The original photo software allowed us to determine the size and number of fragments and the total length of cracks. The results of experiments show that the size distribution of fragments is fitted by the power law related to the scaling properties of the fragmentation scenario.

The fragmentation statistics was studied in recovery dynamic experiments with loaded quartz cylindrical rods using a ballistic set-up (gas gun with a bore diameter of 19.3 mm and a velocity registration system). The sectional glass rod was composed of the transmitting and main parts covered by an elastic shell. The transmitting part was used for realization of uniaxial loading produced by a cylindrical projectile of mass 13.9 g accelerated up to the velocities 6-20 m/s. The mass of the fragments passing through a sieve was obtained by weighting the fragments using the electronic balance HR-202i (accuracy 10^{-4} g). The mass of the fragments corresponding to the maximum of the probability density function varied in the range from $2*10^{-4}$g to $6*10^{-4}$ g. The cumulative fragment size distribution, the number of fragments $N(m)$ with the mass greater than a specified value m were fitted by the power law.

The ballistic set-up was modified to avoid the possible influence of the reflected wave on the fragmentation scenario. The sample was placed into a steel cylinder filled with plastic foam. The sectional glass rod was composed of transmitting, main and outer parts. The fragmentation statistics was analyzed by varying the sample size and load intensity (projectile velocity). The results of experiments indicate that the variation in the sample size and loading conditions does not lead to the change in the probability density function and cumulative mass distribution. The mass of the fragments corresponding to the maximum of the probability density function is independent of the projectile energy.

Finally, cumulative distributions illustrating the relation between the numbers of fragments and their linear dimension are represented as a double logarithmic plot. The linear dimension is defined as a cube root of mass or a square root of area. The distribution is fractal by nature with a power law in the form $N(>r)=Cr^{-D}$, where N is the number of fragments with a characteristic linear dimension greater than $\boldsymbol{r}$. The fractal dimension D varies from 1.6 to 2.0 for a plate and from 1.1 to 1.7 for a rod.

The glass fragmentation experiments have shown that:

- The fragmentation patterns of glass plates are fractal by nature.

- The variation in the fracture mechanism of plates correlates with the changes in the fractal dimension.
- The cumulative mass distribution of the fragments for 2D and 3D samples is described by a power law.
- The statistical number-size distribution for the observed type of fragmentation has a fractal character because the number of objects N with characteristic linear dimensions greater than r satisfies the relation $N(>r)=Cr^{-D}$.

The author would like to acknowledge the Russian Foundation for Basic Research (grant RFBR 11-01-96006, grant RFBR 09-08-99097, grant RFBR 09-01-92005, grant RFBR 11-01-96010).

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MODELLING OF MODERN EVOLUTION OF MIDLAND CRUMPLED AREAS OF THE CENTRAL ASIA. GEODYNAMIC CONDITIONS NEAR CHAGAN-UZUN BLOCK

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Calculations of geodynamic conditions on Altai, in particular, in area Chagan-Uzun block where a large earthquake occurred in 2003 were executed on the basis of the developed evolutionary approach [1]. Geodynamic conditions in this rather small regional area was studied in a context of modelling of modern evolution of areas of the Central Asia as result of a collision of the Eurasian plate with Indo-Asian in the south and North American in northwest. As a structural model of continent the earth block map of Central and East Asia made by K.Z. Seminskiy [2] was taken. Boundary conditions in the region determining a development of deformational process in the region were received from calculations of the global displacement which have arisen as a result of collision processes. In area of the Chagan-Uzun block the vortical structure was formed in all calculations. Directions of shifts and compression in this region appreciably vary in time at the general preservation of vortical character of movement. Calculations of deformation near the Chagan-Uzun block for various combinations of shifts and compression which were set according to the received general character of displacement also were executed. It was found that deformations are localized along the seismically active break, where there was a strong earthquake in 2003.

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EVOLUTION OF ROCK MASSIF NEAR MINE WORKING

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In the framework of the mathematical theory of evolution of loaded medium, the evolution of the massif near a mine working was modeled. The characteristics of the evolutionary process at its transition to the catastrophic super-fast mode were numerically studied. The numerical calculations of the evolution of the massif of the roof over the mined-out space in the mine were performed. The model parameters, which determine the rate of damage accumulation and degradation of strength, were selected by match with a known time period of roof collapse at a given depth of mine working.

DISTINCT FATIGUE RESISTANCE OF PRE-STRAINED ALUMINIUM ALLOYS AND MICROSTRUCTURE SCALING PROPERTIES

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The final objective of this work is to provide the link between the micro-structural behavior and the fatigue behavior of pre-strained aluminium alloys, using the scaling properties of damage induced on the fracture surface.

Different quasi-static and dynamic pre-loadings were performed on two aluminium alloys and their residual fatigue resistance was determined. The alloys have qualitative different fatigue responses to the pre-loadings linked to the material: the Al-Cu alloy demonstrate a sharp decrease of HCF life-time due to the pre-straining whereas the insensitivity of the Al-Mg alloy is clear. That reflects distinct sensitivity to HCF resistance relative to possible FOD.

The investigations made at a 'mechanical' scale allow us to associate the strain energy absorbed during the prior loading with the aspect of the surface and the residual HCF life-time. That makes possible a part-understanding of the results.

The microstructural properties of the fracture surfaces give us other information. The statistical characterization of the fatigue damaged zone was done from the measurement of the surface roughness.

The fracture surfaces for Al-Cu alloy revealed the scaling universality in term of the Hurst exponent. The Hurst exponent invariance reflects the self-similar scenario of damage kinetics. This scenario is related to long-range correlation properties of defects providing damage-failure transition under HCF crack propagation. As a consequence, the role of the states of the pre-loaded microstructure can be analyzed in terms of the initial conditions for the damage parameter. Such analysis explains the fatigue life-time sensitivity to the consecutive loadings.

In contradiction the Al-Mg alloy demonstrates qualitative different scaling behavior: variety of scaling exponent for different pre-strained states and smaller correlation lengths; and for this alloy, it is possible to observe extremely low sensitivity to the pre-loading history.

STRUCTURAL-SCALING TRANSITIONS AND THE MODELING OF DNA DENATURATION

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The work is devoted to research of a role of collective modes in process of DNA double helix denaturation (separation). According to [1] DNA molecule is modelled in the form of two chains of the disks-bases connected by covalent bonds along a chain and hydrogen bonds between the bases in pairs. It was supposed, that the basic contribution in process of opening of base pairs (formation of the defects named «open complexes») is given by hydrogen bonds stretching and breaking, therefore considered model takes into account displacements of the bases y_j along to the hydrogen bonds connected the bases in pairs. The potential V for hydrogen bonds is accepted in the form of a Morse potential, covalent bonds are modeled by potential W. Hamiltonian of the model looks like [1, 2]:

$$H_0 = \sum_{j=1}^{N}\left[\frac{1}{2}m\left(\frac{dy_j}{dt}\right)^2 + W(y_j, y_{j-1}) + V(y_j)\right].$$

In this study process of DNA micro-mechanical denaturation is modeled. The end of one strand is attached to a fixed point while the second strand is connected to an elastic lever. The size of the made force is considered by introduction additional composed an extra term $(c_0/2)(vt\text{-}y_1)^2$ into the Hamiltonian; c_0 – an elastic constant, v – constant speed of a hydrogen bonds stretching. The modeled molecule consisted of 1024 base pairs, calculation was spent for a time interval of 10^6 time units, dependences of bases displacements on time are received. The analysis of DNA dynamics with using of the described potential has confirmed results of work [1, 2] about a role breathers – collective modes of distortion in denaturation process. In this investigation modification of the model with using of bistable potential W in the form of Ginzburg-Landau potential [3] also was done, the obtained dynamic equations are investigated; it was established formation of autosoliton type finate amplitude disturbances.

Research was supported by the Russian Foundation of Basic Research (project № 10-01-96051-r_ural_a).

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EFFECT OF LOW CYCLE FATIGUE DAMAGE IN GIGACYCLE FATIGUE

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In steam generator vessel of nuclear power plants, PWR, Pressurized Water Reactor, typical tee and pipe components are subjected to thermal and mechanical vibration loading histories which are variable and divided into two different regimes: low cycle fatigue and high cycle fatigue regime. The water loop pipes of the steam generator of PWR have been designed to withstand internal pressure. These pipes are subjected to long time repeating cyclic loads from cold temperature water injection. Moreover, the steam generator creates high pressure steam flowing through the tubes to promote the turbine, giving rise to a higher frequency vibration. It results in another kind of damage with low load amplitude within elastic limit and high frequency. The tube vibration can be regarded as very high cycle fatigue damage.

Carbon-Manganese steels, A42 and A48 (French standard) are often used in such applications. In order to investigate the cumulative damage of low cycle fatigue in gigacycle fatigue, the gigacycle fatigue tests have been executed with ultrasonic fatigue test machine after LCF fatigue cycles damaged. The specimens are designed into hourglass form due to the test working at resonance state with 20 KHz frequency. The prior LCF damage has been completed in diametral strain controlling. The comparison of VHCF and cumulative fatigue test results shows that LCF load can influence the VHCF strength, in agreement with the fractographic analysis.

Continuum Damage Mechanics model is employed to estimate the fatigue damage of LCF and is extended to VHCF regime. Moreover, the effect of LCF load on VHCF is studied by an improved cumulative damage model.

MAXIMUM ENTROPY IN A NONLINEAR SYSTEM WITH 1/*F* NOISE

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The dynamic of fluctuations with a $1/f$ power spectrum at two coupling phase transitions in a lumped system may be described by the system of nonlinear stochastic differential equations:

$$\begin{aligned} \frac{d\phi}{dt} &= -\phi\psi^2 + \psi + \Gamma_1(t), \\ \frac{d\psi}{dt} &= -\phi^2\psi + 2\phi + \Gamma_2(t), \end{aligned} \tag{1}$$

where ϕ and ψ are *the* dynamic variables (order parameters), their sum $\psi + \phi$ and the difference $\psi - \phi$ are related to the order parameters of the subcritical and supercritical phase transitions in the Landau theory. Γ_1 and Γ_2 are δ-correlated noises with the normal distribution (white noises). The second equation in System (1) is a governing equation. We find the local maximum of information entropy $H = -\sum_n P_n \log(P_n)$ for the probability distribution function $P_n(\psi^2)$ of the variable defined by the governing stochastic equation [1].

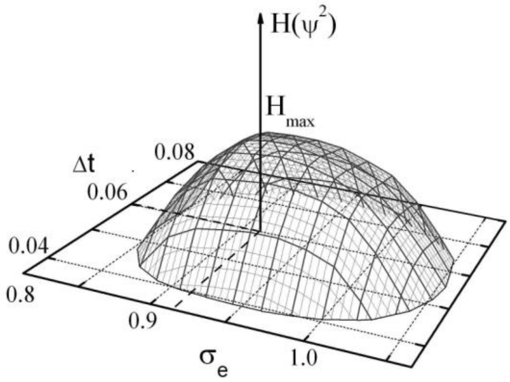

Fig. 1. Maximum entropy in the variables defining the tuning of System (1) at the numerical integration (σ_e is the intensity of the external noise, Δt is the integration step).

It is shown that the coordinates of the maximum define the critical state of the system, corresponding to the noise induced transition at which the power spectra of the fluctuating variables are inversely proportional to the frequency. The existence of the maximum entropy indicates the stability of random processes with 1/*f* power spectrum.

The expressions for the entropy in nonadditive statistics are discussed.

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DEFORMATION AND FRACTURE OF HIGHLY-POROUS CERAMIC MATERIAL BASED ON OXIDE PARTICLES

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It have been studied the porous structure and its influence on the mechanical behavior of zirconia nanoceramic with the porosity up to 70%. It was shown that there is a critical value of porosity in material with unimodal pore distribution and material divides into two sub-systems, being variously deformable under external loading. It have been shown for ceramics with bimodal pore distribution, the lower is its magnitude, the higher is the index of power function, exponentially decreasing with the increasing porosity. In such materials there occurs the micromechanical instability of rod-like structures, obtained after sintering of porous body, with their considerable macro-deformation as structural elements, which may be realized in the elastic area. It has been found out the correlation between the sizes of crystallites and porosity, which associated with transition of the isolated porous structure to the continuous one and the porosity of 20%, corresponds to the first percolation threshold.

It has been developed sintering methods of high-porous ceramics with special nano- and mesosructures of porous clusters. These materials have very similar properties (mechanical behavior and pores morphology) as compare with natural bones.

INVESTIGATION OF THE MULTITUDE OF LOCALIZED INSTABILITIES UNDER DYNAMIC DEFORMATION

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This paper deals with an experimental study of the deformation behavior of materials under dynamic loading. The process of perforation of a target involving plug formation and ejection at impact velocities of 101 – 260 м/с was investigated using a high-speed infra-red camera CEDIP Silver 450M with sensitivity ~25 mK (at 300K), spectral range 3-5 micron and maximum frame size 320x240 pixels and a VISAR velocity interferometer system. The original ballistic set-up for studying perforation was used to test A6061 alloy 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.

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.

CRITICALLY SELF-ORGANIZED DEFORMATIONAL SYSTEMS. PROBLEMS OF DESTRUCTION PROGNOSIS

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The general nonlinear properties of processes of not elastic deformation and destruction of loaded solids and media, and also similar properties of numerical solvings of nonlinear system of the equations in the private derivatives modeling deformational processes are discussed. Auto-modeling property of processes of accumulation of non elastic deformations / damages to all hierarchy of scales from internuclear distances and up to formation of tectonic breaks in an earth's crust in many thousand kilometers causes qualitative similarity of scripts of destruction irrespective of scales of deformational process and rheological properties of media. Such general properties of deformable systems are: spatial localization of accumulation of damages/non elastic deformations in all hierarchy of scales, the further localization of deformational process in time as superfast autocatalysis process - a regime with an aggravation, presence of slow dynamics (formation of deformational fronts - slow movements), and also migration of deformation activity owing to the long existential correlations covering all hierarchy of scales. Thus, process of destruction develops as a sequence of accidents of increasing scales up to macroscopical. It is shown, that the self-organized criticality of any deformable systems does not exclude an opportunity of a prediction of time and a place of the future catastrophic event. As indicators of such large-scale event the following processes can serve: 1) decreasing of deformational activity in a near vicinity of a formed main crack or a break; 2) Generation of fronts of damages in the nearest zone of the formed center of destruction and their "running off" to a place of a formed main crack (break).

STATISTICAL SAMPLING IN VOLUME ELEMENTS FOR EVOLUTIONARY STRUCTURE-PROPERTY RELATIONS

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Modeling dislocation plasticity in crystalline metals over a broad range of length and time scales is quite challenging due to the long range fields and complexity of many body interactions. This talk will provide a perspective regarding nuances of the role of heterogeneity in modeling microstructure evolution. Particular attention is devoted to issues related to computing at the scale of a representative volume element (RVE) size for evolving microstructure that meets requirements of statistical homogeneity and has relevance to problems of interest involving field gradients or rare event phenomena with long correlation length scales. Conventional goals for homogenization based on spatial distributions of microstructure attributes over a representative volume element (RVE) are useful to achieve a mean response function such as elastic stiffness. However, if the goal is to characterize the fluctuations of the response (higher moments) within the RVE, it is fruitful to pursue joint correlations of microstructure attributes with responses, a form of biased sampling or importance sampling. Of particular interest are phenomena with very large RVEs that are not amenable to direct computation. The large simulation scales required to build up statistical homogeneity associated with rare event phenomena motivate the use of multiple realizations of statistical volume elements (SVE) for evolving microstructure. Information related to the spatial distribution of "hot spots" of response, such as driving forces for small cracks or storage of elastic energy, can be passed to coarse scale descriptions in multiple ways. These include use of marked correlation functions, extreme value statistics, and hierarchical multiscale modeling algorithms that embed distributions of computed responses into the coarse scale description as kinematic internal state variables. Examples are presented for dislocation avalanches during nanoindentation and polycrystalline fatigue.

STRUCTURAL-SCALING TRANSITIONS IN MESODEFECTS ENSEMBLES AS MULTISCALE MECHANISM OF PLASTICITY AND FAILURE

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Statistical theory of evolution of typical mesoscopic defects (microcracks, microshears) allowed us to establish new type of critical phenomena in solid with defects – structural-scaling transitions, to develop thermodynamics of solid with defects and to propose the phenomenology based on generalization of the Ginzburg-Landau theory and constitutive equations. The key results of statistical theory and statistically based phenomenology are the establishment of two order parameters responsible for structure evolution – the defect density tensor (deformation induced by defects) and the structural scaling parameter, which reflects the scaling transition in the course of nucleation and growth of defects, and generation of characteristic collective modes of defects responsible for the relaxation (shear transformation zones -STZ) and failure (damage transformation zone -DTZ). These modes have the nature of the solitary wave and blow-up dissipative structure and provide the mechanisms of plastic relaxation and damage-failure transition and can be excited in the resonance regime in dynamically loaded and shocked materials. Dynamic, shock wave experiments and structural study supported the linkage of the evolution of these modes with material responses in large range of strain rates and loading intensity and allowed us to propose the interpretation of following effects [1,2]:

(i) The understanding of links between the types of collective modes allowed the explanation of transitions between quasi-brittle, ductile and bulk nanocrystalline state, the role of scale characteristics of materials in these transitions, the link of dynamics of collective modes with relaxation properties and damage-failure transition. The transition from polycrystalline to bulk nanocrystalline state is accompanied by the degeneration of collective orientation modes that have the structural image as localized shear areas. The formation of "nonequilibrium dislocation lattice", degeneration of collective orientation modes of defects changes the mechanisms of momentum transfer (the violation of the Hall-Petch law).

(ii)The mechanisms of failure wave generation and propagation that has the nature of delayed failure with the delay time, which corresponds to the time of the excitation of blow-up collective modes (DTZ) in the microshear ensemble.

(iii)The self-similarity of plastic wave fronts for polycrystalline materials with different grain sizes, fourth power universality of the steady-state plastic front as the consequence of the subjection of the relaxation kinetics to the dynamics of the STZ was confirmed both theoretically and experimentally

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EXPERIMENTAL RESEARCH OF GERMINATION OF A CRACK AT GIGACYCLIC FATIGUE

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Recently there was a necessity to conduct fatigue tests for the bases of test exceeding 10^9 - 10^{10} cycles loading are so-called gigacyclic fatigue. It is connected by that the resource loading many responsible designs working in a mode of cyclic loadings, exceeds standard norms. In turn gigacyclic fatigue area has a number of features where special interest represents a boundary corresponding to number of cycles $N \approx 10^9$. At passage of this boundary there is a change of mechanisms of origin and development of fatigue cracks; on curve fatigue in this area loading ruptures are formed. It is noticed, that the environment role essentially increases in this area of number of cycles loading and by that use of classical laws of physics of destruction is at a loss.

The scaling laws, which describe power-law relationships between fatigue crack growth rate per cycle $\mathrm{da/dN}$ and the stress intensity range $\Delta \mathrm{K}$, is the subject of intensive experimental and theoretical study. The significance of understanding is in the life prediction according to the nature of self-similarity in the Paris law:

$$\frac{dA}{dN} = C(\Delta K)^m ,$$

where C and m are experimentally determined scaling-law constants. This relationship has been verified over a wide range of growth rates and provides the basis for the life prediction in the framework of damage tolerance approach. Another reason for the study of self-similarity nature is the deviation from Paris's law kinetics with the power m~3-4 in the area of gigacycle fatigue.

The explanation of the Paris law universality was proposed in [1] under consideration of multiscale evolution of microshears ensemble at the crack tip (process) zone, which has the feature of structural-scaling transition in dislocation substructures [2]. Similar to critical phenomena the damage accumulation under the crack advance manifests the criticality signs and depends on the characteristic scales, where multiscale dislocation substructures reveals coherent behavior as the precursor of fatigue crack propagation. This assumption concerning the criticality conditions was used in the statement of experiment for the explanation of the fatigue crack path scenario in steel notch specimen loaded in gigacycle regime. In work samples from high-strength steel R4 were exposed to fatigue tests in the conditions of a symmetric stretching – compression with frequency 20 kHz. The crack advance (realized under constant value of ΔK) was linked with the scaling properties of defects induced roughness estimated according to the New View morphology data in the process zone for different stages of crack path. The intermediate nature of scaling law is discussed according to the scales where the defect induced roughness reveals long-range correlation properties.

In work the blanket with fatigue microcracks is investigated, and results of work allow us considerably to expand representations about fatigue durability of materials at gigacyclic fatigue and to give recommendations influencing durability of materials.

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THE COLLAPSE OF THE WAVES OF LOCALIZED PLASTICITY UNDER THE FAILURE

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The behavior of localized plastic flow sites occurring at the final flow stage was investigated. Our previous works testify that the plastic deformation tends to localize on the macro-scale level over the entire flow process [1]. Various localized plasticity patterns would emerge in the test specimens with the pattern type being determined by the work hardening law acting at the given flow stage.

The quantitative characteristics of localized plastic flow process were determined for a wide range alloys having FCC, BCC and HCP crystal lattice. Specimens were tested in tension at a constant rate in an Instron-1185 test machine at 300 K. The loading diagrams obtained for investigated materials were analyzed. The working stress σ and the plastic strain ε are related by the Ludwic equation as $\sigma = \sigma_0+\theta\varepsilon^n$. Here $0 \leq n \leq 1$ is the hardening exponent (pre-failure stage for n values in the range $0 \leq n \leq ½$). The observations of localized plasticity domains were performed by the method of speckle photography [1].The macro-localization behavior of deformation were investigated over the entire loading diagram obtained for the deforming sample. A correspondence rule has been established for a range of materials in the monograph [1], which relates the macro-localization patterns emergent in the deforming sample to the respective plastic flow stages.

On the base of experimental evidence the quantitative characteristics of localized plastic flow process were determined for a wide range of materials. It is found that equidistant mobile deformation sites occurring at the linear stage would form a running wave. Immobile sites occurring at the Taylor parabolic work hardening stage form a space periodic pattern. Sites distributions observed at the pre-fracture stage exhibit no space periodicity. A maximal amplitude zone would form on the location of future necking. And the hitherto immobile domains (nuclei) would become mobilized and start traveling in concerted manner, with their motion rates being correlated spontaneously. When extrapolated, the plots would intersect for $n \leq ½$ at one and same point. The latter point is the pole of this bundle of straight plots. Its co-ordinates are readily defined for the test specimens. Of particular importance is that the bundle pole pinpoints the location of future fracture. Using kinetic characteristics of localized deformation sites obtained for the pre-fracture stage, the place and time of future failure can be predicted. A satisfactory match is observed between the calculated and real data. Clearly, the difference between the calculated and real co-ordinates and times is not greater than 7 percent. On the base of this evidence a new method for predicting material fracture can be developed. This would facilitate prediction of the place and time of future fracture.

Thus, the process of necking end failure zone nucleation results from the complicated concerted motion of localized plasticity nuclei (collapse of the localized plastic flow wave), which causes the nuclei to concentrate in the zone of viscous failure, with each nuclei moving at a constant rate of its own.

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MULTISCALE TECHNIQUE FOR LOCALIZED STRAIN INVESTIGATION IN METAL ALLOYS AND CARBON FIBER REINFORCED COMPOSITES BASED ON DATA OF STRAIN GAUGING, SURFACE STRAIN MAPPING AND ACOUSTIC EMISSION

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A combined method to investigation of localized deformation processes in notched and surface hardened metal alloy specimens as well as notched carbon fiber reinforced composites is applied in order to reveal characteristic stages of strain and fracture. Stress concentrators have the shape of a circular hole and edge crack of various size as well as three semicircular notches being located at different distance from each other. Surface hardening was employed in order to provide surface cracking which can vary substantially stage pattern of deformation development. Carbon fiber reinforced composites with notches of different size were also tested in order to illustrate the difference in deformation behavior between metal based specimens and reinforced polymeric composites. Use of simultaneous registration has allowed us to register and compare parameters under analysis during entire time of the experiments. The reasons of similarity and difference of the results are shown and discussed. It is offered to apply the obtained results for the aims of non-destructive testing of structural materials being based on revealing characteristic stages of strain development and revealing prefracture stage.

NONLINEAR WAVES OF LOCALIZED PLASTIC DEFORMATION IN A LOADED SOLID TREATED AS A MULTISCALE HIERARCHICALLY BUILT SYSTEM

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Single-scale approaches used in continuum mechanics (macroscale level) and dislocation theory (microscale level) treat plastic deformation as a purely dissipative process. A description of a loaded solid as a multiscale hierarchically built system makes it possible to predict theoretically and confirm experimentally the fact that sell-organization of localized shear strains at different scale levels is responsible for propagation of nonlinear waves of localized plastic deformation in the loaded solid and for dissipative plastic flow induced by motion of dislocations at the microscale level.

Using high-resolution scanning devices, we have detected propagation of shear strains, channeled along conjugate directions of maximum tangential stresses in the surface layer of the specimen. The channeled shear strains give rise to macroscopic localized plastic deformation bands in the bulk of the material. The bands generated at regular intervals are evident as a front of the nonlinear wave of localized plastic deformation propagating along the loading axis of the specimen.

Using methods of physical mechanics and nonequilibrium thermodynamics combined in an integrated framework, we have developed a theory of nonlinear waves of plastic deformation in a loaded solid. An analytic expression is derived for the channeled defect flux in the surface layer of the uniaxial tension specimen, allowing for boundary conditions of an invariable loading axis. The period and length of the nonlinear transverse wave of localized plastic deformation are shown to increase with the specimen length. This finding is consistent with experiment. An increase in the strength of the surface layer causes the length of the nonlinear wave to shorten. In addition, the wave is dispersed in to a series of short-wavelength nonlinear debris evident as double spirals propagating in the surface layer along the loading axis.

The effect of the nonlinear waves of localized plastic deformation on the mechanical characteristics of solids exposed to different kinds of loading is discussed. It is shown that propagation of any kind of the nonlinear waves of localized plastic deformation in a solid under loading is accompanied by decreasing of its mechanical characteristics. Special treatment of a solid surface layer allows one to block the nonlinear waves of localized plastic deformation and to increase substantially all its mechanical properties.

EARTHQUAKE SOURCE NUCLEATION AS EVOLUTION OF BLOW-UP REGIMES IN MESODEFECTS ENSEMBLE

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The concepts were developed during the last time (Sadovsky, 1989; Knopoff, 1993; Bak, 1996; Turcotte, 1997; Sornette, 2000; Rundle et al., 2000; Kossobokov et al., 2002; Tyupkin, 2004a,b,c) that the nucleation of a strong earthquake can be described as the behavior of a physical system in the vicinity of a critical point. It implies that at the approaching to the moment of a strong earthquake the individual behavior of crustal elements becomes insignificant and collective processes encompassing all space–energy scales of the system arise in the nucleation region of incoming earthquake. In particular it is resulted in correlation of earthquake activity in the area of incoming strong earthquake. Recent studies hypothesize the important associated phenomenon: the area over which earthquake activity is correlated varies in time and might grow during a main shock preparation (Zaliapin et al., 2003; Tyupkin and Di Giovambattista, 2005).

In accordance with the model of avalanche-unstable fracture (Myachkin et al., 1975) the source formation process consists of three stages. Under the influence of slowly increasing tectonic stresses, a more or less uniform (diffuse) accumulation of cracks in a rock volume Ω and their gradual growth take place at the first stage. As the density of cracks ν reaches a critical value $\nu_{cr}^{(1)}$ in a relatively small region $\Omega_S \subset \Omega$, the state of the medium enters the second stage, which is characterized by an appreciable increase in fracturing in the region Ω_S and growth of this region. This stage is associated with formation of a potential earthquake source, and the region $\Omega_S\ t$ with the potential source region. The total strain rate in $\Omega_S\ t$ increases due to the strain contribution along crack edges. The main physical feature of the potential source region is that the crack interaction increases the probability of fracturing in this region relative to that in the case of $\nu < \nu_{cr}^{(1)}$; i.e., this region is characterized by the process of fracture self-organization. Finally, the third stage is distinguished by the onset of unstable deformation localized in a narrow zone of the developing fracture. This stage begins as the density of cracks reaches a second critical value $\nu_{cr}^{(2)}$ and develops generally due to elastic energy release.

Important defect of modern concepts in earthquake source physics (Rundle, 1997; Tyupkin, 2005; and others) is inability of the description of third stage of earthquake development, when in the local potential source region the density of mesodefects develops in the blow-up regime.

In this work, the evolution of local damage zone in potential earthquake source region and self-similar features of seismic events are analyzed in the framework of the conception of structural-scaling transitions in mesodefects ensembles. It was shown, that this concept allows the description of the third stage of earthquake evolution and self-similar features of seismic events (Gutenberg-Richter law, Omori law) are connected with dynamics of blow-up structures in mesodefects ensembles.

Research was supported by the Russian Foundation of Basic Research (grant № 10-05-96065-р_урал_а) and Program of RAS Presidium № 09-П-1-1010.

MODELLING OF MODERN EVOLUTION OF MIDLAND CRUMPLED AREAS OF THE CENTRAL ASIA. GEODYNAMIC CONDITIONS IN BAIKAL RIFT ZONE

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On the basis of the developed evolutionary approach [1] calculations of modern evolution of areas of the Central Asia as result of a collision of the Eurasian plate with Indo-Asian in the south and North American in northwest were executed. As a structural model of continent the earth block map of Central and East Asia made by K.Z. Seminskiy [2] was taken. In calculations varied the attitudes of strength characteristics of rigid blocks and pliable zones. It was found out that the best consent with observably displacements for areas of Baikal rift zone and northeast of Asia turns out at rather close relations of durability of rigid blocks and more pliable damaged zones. For a southern and southeast part of continent, it is especial in mountain areas of Tibet and Tyan-Shan these relations already reach essentially big values. In the further calculations this parameter will be depending on a density of seismic breaks for the appropriate regions. Maps of modern displacements of areas of the Central Asia are constructed. Settlement fields of displacement appeared in the good consent with available supervision. So, in the field of Baikal rift global shift is observed. In the areas which are taking place to the north about Baikal, a direction of movement from northeast on a southwest, while for areas to the south about Baikal global displacement carry a return direction. At a premise of a reference mark in the centre about Baikal, character of displacement shows typical rift zone - a direction of displacement of northern and southern coast is opposite, i.e. rift is opening.

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SCALING PROPERTIES OF THE FRACTURE SURFACE OF ULTRAFINEGRAINED ALUMINUM ALLOYS

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Currently, there are many experimental results proving efficiency of grain refinement and improvement of mechanical properties of a number of industrial alloys by severe plastic deformation (SPD). Despite the progress in this area the development of new methods of SPD remains an actual scientific and technical problem. The authors carried out a series of studies on structural and phase transformations of aluminum conventional alloys under loading in the complex fields of mechanical shear and shock wave. The investigation of the mechanical and physical properties of the samples from A3003 and A7075 alloys produced by new method of high-speed deformation - dynamic channel-angular pressing (DCAP) was carried out. As the basis of DCAP the equal channel angular pressing (ECAP) was used. In the experiments, the samples are speeded up using a gun to velocities (V) of 100 to 500 m s^{-1} providing high strain rates of 10^4-10^5 s^{-1}.

The results showed that fragmentation processes occur actively in A3003 alloy during one pass (N=1) at the velocity V=150 m s^{-1}. The increasing of V up to 300 m s^{-1} by one pass promotes formation of the mixed structure with low-angle and high-angle boundaries. The increasing of V up to 300 m s^{-1} by N=4 intensifies the process of submicrocrystalline structure formation. Subdivision of the initial structure occurs due to bending of the crystal lattice and active grains sliding. Thus one can assume structure formation is realized by the competition of fragmentation and dynamic recrystallization at higher strains (N=4) that leads to low-angle boundaries transformation in to high-angle boundaries, reducing chare of the mixed structure, and causes grains coarsening. Average size of structural fragments is 600-650 nm irrespective of loading conditions.

According to transmission electron microscope (TEM) data already after 1 cycle of DCAP at V=150 m s^{-1} fragmented structure with average size of crystallites of 200 nm is observed in case of A7075 alloy. The structure is characterized by high dislocation density, defused nonequilibrium high-angle grain boundaries. The mechanism of ultrafinegrained (UFG) structure formation is plastic deformation in A7075 alloy.

To determine the mechanical characteristics of deformed samples quasistatic tensile tests at room temperature at a strain rate 10^{-3} s^{-1} were carried out. The results showed that tensile strength (σ_B) increases by 25%, yield strength ($\sigma_{0.2}$) is 2.4 times higher, elongation to failure (δ) decreases from 40% to 13 % in comparison with initial coarse grained sample for

A7075 UFG DCAP samples. For A3003 alloy samples after DCAP σ_B observed is by 20-40% and $\sigma_{0.2}$ by 50-60 % higher than for coarse grained sample.

The fracture surfaces of materials were examined. It was established that the nature of the surface relief is “pitted”. There is a satisfactory agreement between the “pits” size and an average grain size. This indicates that there is fine fracture along high-angle grain boundaries. Transition from plastic deformation to failure is considered as a structural-scaling process, during which defect structure evaluates in a self-similar manner. This arises in the formation of self-affine relief on the fracture surface. With the help of high - resolution microscope, interferometer-profilometer “NewView 5010” a 3D-data about relief was obtained and analyzed on the basis of fractal concept to find scaling characteristics of fracture surface formation, in particular, the Hurst exponent and scales, at which self-affine relief is observed.

TEMPERATURE EVOLUTION IN SUBMICROCRYSTALLINE METALS UNDER CYCLIC LOADING

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During the last decades, the enhanced ability to detect temperature evolution in the crack tip, along with a great interest in applying of continuous thermodynamics formulae to the investigation of defect evolution under cyclic loading. The heat generation process depends of both the thermoelastic effect and plastic energy dissipation. The theoretical and experimental investigation of this problem can be useful for explanation of many actual problems in fracture mechanics such as monitoring of fatigue crack propagation, energy storage in defect ensemble in process zone.

In this work, extending previous results of the research group in Perm, we coupled the experimentally investigation of temperature evolution under cyclic loading with a statistical description of the mesodefect ensemble. It allowed us to propose a thermodynamic internal variable model of heat dissipation in metals.

Our experimental investigation used an infrared camera CEDIP Silver (thermal resolution up to 0.1 mK and maximum framing rate up to 20kHz) shows that the appearance of mesoscopic defect structures consisting of strong interacting defects lead to the specific thermal behavior. It has been shown, that under cyclic loading the kinetics of energy accumulation in the material essentially depends on the grain size. Cyclic experiment was carried out accordingly to Luong`s scheme. The material under investigation was titanium Grade 2 with two different mean grain sizes (30 μm and 0.3 μm). The scheme includes step-by-step loading of the sample. In our experiment we used an asymmetrical cycle (asymmetrical factor 0.1 or -1) with increase in stress amplitude on 10 MPa per each step. The nanocrystalline samples exhibit high energy dissipation ability under small stress amplitude and have no essential jump in the speed of energy dissipation at transition through fatigue limit.

Our experimental results are indicative of the ability of submicrocrystalline samples to more effectively employ the structural (configurational) channel of energy absorption during deformation, involving the entire deformed volume into this process. The same factor accounts for the quasi-brittle character of fracture in the submicrocrystalline samples, which proceeds via the formation of a local connected cluster of the grain-boundary defects.

Work is partially supported by program of the Russian Academia of Sciences (09-P-1-1011).

PARTICLE METHOD AS A TOOL OF PHYSICAL MESOMECHANICS FOR MULTISCALE SIMULATION

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A modern theoretical approach used for description of heterogeneous solid is based on one of two concepts of representations of the medium: continuum or discrete. Notwithstanding the fact that discrete concept reflected discrete structure of matter more correctly at different spatial scales, during following one and the half century continuum concept prevailed. It was because of this concept gave the advantage of analytical description. Onset of computer era and development of numerical methods in 1950th initiated remarkable progress of discrete approach, which started to develop by self-dependent way. Depending on the application field and the problem under consideration, these methods could be divided into two main types: particle methods (PM) and cellular automaton (CA) methods. The latter are mainly used to study thermodynamic processes connected with change of material phase state on cells fixed in space while methods belonging to the first group mostly are applied to investigate mechanical (or thermomechanical) aspects of material behavior (including fracture) under complex external actions. PM methods are very diversified and in reality include not only «true» representatives of discrete approach in mechanics, but also some approaches for solving continuum based equations for dynamics of solids and fluids. Moreover, at present some advanced realizations of conventional numerical methods of continuum mechanics like particle finite element method are referred to the class of particle methods as well. At the same time «true» particle methods are based on representation of simulated material or media as an ensemble of interacting bodies (particles) having finite size and defined shape. Depending on the method, evolution of the ensemble is governed by either Newton's equations of motion or system of equations for potential energy minimization.

«Newtonian» approach was independently proposed by P.A. Cundall and Greenspan at the end of 1970s. At the present time these two similar methods have been developed into a quantity of methods and models, which are referred to collectively as discrete element method (DEM). DEM is the most well known realization of discrete concept in mechanics. It has been successfully used in various fields of material science, civil engineering, industry and geomechanics for simulation of deformation and fracture of various materials and media.

The main idea of DEM started from molecular dynamics method, which was developed to study wide range of problems at the atomic level. The both methods use Newton's motion equations for translational degrees of freedom of elements or atoms. Therefore, similar to the molecular dynamics method, an important fundamental problem in

DEM is development of particle interaction force/potential, which provides the element ensemble response conforming to the simulated material or media. In spite of considerable progress in DEM formalism, up to now two-particle forces are mainly used for description of particle interaction.

Numerous applications of particle method to solution of various problems of physical mesomechanics are shown in this paper.

FEATURES OF FRACTURE DEVELOPMENT OF ANISOTROPIC MEDIA AT HIGH-VELOCITY LOADING

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Development of technologies of creation of materials with the set characteristics impulses to use features of anisotropy in all modern branches of techniques. The effective usage of elements of designs, whose functioning is possible only by optimization on parameters, is impossible without use of materials with a primary orientation of properties. It is necessary to notice that in the majority of modern works of an axis of coordinates coincide with the main axes of symmetry of a material. The urgency of researches of behavior at blow is defined by requirement for noegenesis about properties and forecasting of reaction for dynamic loading of elements of designs from anisotropic materials.

In research the model of elastic-brittle behavior of a material was used. As criterion of transition of an anisotropic material in the destroyed condition it was used criterion of Vu. Penetration of the steel compact projectile in anisotropic target with various orientations of elastic and strength properties was modeled. The range of velocities of interaction was from 750 to 3000 km/s. It has been shown that application of anisotropic materials with the set gradient of strength properties is an effective method of creation of designs. The low density and high resistibility to high-velocity loadings allow using organoplastic in a wide spectrum of application.

MESOMECHANICS OF SURFACE PHENOMENA IN NONHOMOGENEOUS MATERIALS

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Extensive experimental studies for many materials show that the free surface being flat in a prestrained state undergoes pronounced out-of-plane displacements as soon as load is applied. A characteristic feature of this phenomenon referred to as strain-induced surface roughening is that groups of grains instead of single grains are involved in a cooperative motion to form hills, hollows or folds on the surface.

While a great deal of pertinent experimental evidence has been amassed, the problem of identifying the mechanisms involved and the factors responsible for the morphological changes on a free surface is a debated topic among researchers. Even though local plastic deformation within individual grains is accomplished by motion of dislocations, the cooperative behavior of deformation modes is of nondislocation nature and can hardly be described by the dislocation theory alone. Construction of adequate models for the surface roughening in the framework of classical mechanics also presents some difficulties, particularly for an isotropic homogeneous material under uniaxial tension. On a flat surface free from the action of external forces, the stresses likely to cause out-of-plane displacements are zero. It has become apparent that deformation and fracture found on the surface of loaded solids are of complex character and have to be analyzed not only at micro- and macroscale levels, but at intermediate scales as well. It was a motivation for us to analyze the surface roughening phenomenon numerically, using a mesomechanical approach.

Mesomechanics treats media with interfaces of different scales and configurations and with different properties giving rise to specific non-homogeneous deformation modes at various scale levels. In this work, a 3D numerical analysis of surface roughening in polycrystalline and coated materials under uniaxial tension is performed with explicit account for their microstructures. The results obtained suggest that the internal interfacial inhomogeneities are responsible for the formation of the surface relief on the examined free surface. Originally, the free surface is flat, but it undergoes morphological changes at the outset of the loading process. The width of the resulting relief folds exceeds the characteristic size of polycrystalline grains and interfacial asperities. Applied loading causes the height of the relief folds to increase, but the qualitative pattern remains unchanged until one deformation mechanism gives way to another (for instance, until an elastic–plastic transition takes place). The influence of internal interfaces on the deformation relief is found to diminish nonlinearly with the depth below the free surface.

The work is supported by the President of the Russian Federation (Grant MD-6370.2010.1) and Russian Foundation for Basic Research (Grant 10-08-00084-a).

HIGH CYCLE MULTIAXIAL FATIGUE STRENGTH CRITERIA AND MICROSTRUCTURALLY RELATED MODELING OF METALS

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High cycle fatigue (HCF) of materials and structures is a key problematic in engineering for safe structural design. Years of active research since the end of the 19th century lead that field to a mature state. For multiaxial proportional loadings, fatigue life prediction methods are well established and give reasonably good results when compared to experimental results. However, for highly complex loadings , some key experimental features are still not well understood and captured (non-proportional loadings, non-linear damage accumulation under variable amplitude loading for example). In addition, microstructurally sensitive fatigue modeling are needed to further extend the loop of fatigue strucural design towards material optimisation. This paper presents microstrurally related durability approaches developed in the laboratory and proposes an overview of the major multiaxial fatigue life prediction methods in the HCF domain focusing on their fundamentals. Those fundamentals are discussed for multiaxial proportional and non-proportional fatigue loading. Using a continium mechanic framework and polycrystalline plasticity modeling, the microplasticity developping in CFC artificial microstructures under complex loading has been investigated using FEA. Based on the heterogeneity of the local mechanical response, the main hypothesis of multiaxial fatigue life criteria will be discussed. Further examples of microstrurally based durability apporaches developped in the laboratory will be presented.

PHYSICS, MECHANICS AND SYNERGETICS OF IN-SERVICE TITANIUM ALLOYS FATIGUE CRACKING

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It is well-known phenomenon of titanium alloys in-service fatigue cracking. During fatigue crack propagation because of difference in materials structure it is possible to realize a wide range of mechanisms of fatigue cracking. The mechanism of quasi-cleavage with facetted pattern formation was discovered, and it was shown that in this case the durability and fatigue crack growth period have minimum. This situation thoroughly studied in area of low-cycle-fatigue (LCF) that has allowed to reveal sensitivity of titanium alloys VT3-1 and VT8 to dwell time of cyclic loads that is typical for in-flight loading of compressor disks. Two types of lamellar and mixed globular-lamellar material structure of titanium alloys were investigated.

The paper discussed problem of dwell-time duration and high level of R-ratio influence on the durability and fatigue cracking of titanium alloys.

To understand in-service material fatigue cracking with crack origination at the surface or subsurface it was introduced bifurcation diagram based on the synergetic approaches. We should point out that cracks defined as subsurface nucleate in a not strengthened material and at the stresses never above the fatigue stress σ_{w2}: at this stress level cracking never began at the specimen surface earlier than after 10^6—10^7 loading cycles. This new area for materials fatigue behavior was named Very-High-Cycle-Fatigue (VHCF) or Gigacycle-Fatigue.

The problem of subsurface fatigue cracking for titanium alloy VT3-1 has been discussed based on the acoustic emission (AE) monitoring material behavior at the moment of crack origination and short crack propagation. The subsurface crack origination takes places in titanium alloys because of hydrostatic stress-state, material local volume compression and twisting under cyclic loads and gas diffusion in area of a first weakened facet (FWF). Intensive analyses of FWF orientation have shown that it is primary α- grain slip by the basal plain.

The material transition from one to another manner of cracks initiation is indication that S-N curves have to be differenced from on to another for different position of crack initiation site. That is why bimodal durability distribution is essential in this case for different manner of crack initiation.

The paper discussed of in-service and in-fatigue-tests cracking of titanium compressor disks of VT3-1 titanium alloys under long dwell-time in cyclic loads (more than 45 min), specimens' test of this alloy and systematic behavior of material cracking in LCF and VHCF, including tests results at the frequency 20 kHz has been demonstrated.

MODELS OF GENERALIZED MEDIA MECHANICS AT THE MESOSCALE

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Some experimental and analytical investigations show that for the macroscale description the Cosserat moduli are very close to zero for most materials [1]. But it must not be the case for the other length scales. The physical reason for such an approach is the evidence that conventional dislocation-based mechanisms of plastic deformation seem to have difficulties due to restrictions of dimensions. Whereas there are reasons to assume that the rotational mechanisms may play a very important role due to, for example, pronounced grain boundary sliding and active behavior of interfaces in such materials. This is of particular importance for the mesoscale where the influence of material internal structure can not be neglected.

Microstructure investigation of materials with submicrocrystalline and nanostructures loaded in tension and compression has revealed development of rotation-shear mechanisms of plastic deformation promoted by the initial fine grain structure [2, 3]. Such features of mechanical behavior can not be explained by dislocation mechanisms of their deformation only. Hence, a realistic model for these materials must take into account the basic contribution of the rotational mode of inelastic deformation in the mechanical behavior.

We shall restrict our consideration to the mesoscale only with taking into account the influence of microstructure from the micro scale by means of rotational degrees of freedom. We assume that at the initial stage of loading the conventional elasticity can be adopted. But starting from some critical point (specified by stress or strain) plastic deformation appears. As it grows the additional Cosserat moduli increase smoothly also. This results in the appearance of asymmetric force stress, couple stress, and rotational degree of freedom. Under some conditions plastic curvature can also appear that gives rise to restrictions of not only force stress but of couple stress as well. This means that the new moment moduli are not the material parameters but functions which reflect at the mesoscale averagely the development of microscopic processes in non-stable nanostructured material under loading.

Using a well known finite difference scheme described e.g. in [4] a computer code was written for solving the above mentioned set of dynamic equation (with taking into account inertia terms). Some results of numerical calculations will be presented and discussed. For example, results of test calculation that reveal the features of strain localization which the model can describe (the thickness of the bands).

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FAULT NETWORK RECONSTRUCTION FROM SEISMICITY, MULTIFRACTAL STRESS ACTIVATION TRIGGERING OF FAILURES AND EARTHQUAKES: TOWARDS OPTIMAL PREDICTION OF TIME-TO-FAILURE IN HETEROGENEOUS MATERIALS

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The talk will be divided in three parts. First, we present a new method of data clustering applied to earthquake catalogs, with the goal of reconstructing the seismically active part of fault networks. The key challenge is to relate damage in the crust (earthquakes) to the strain localization zones (faults). We first use an original method to separate clustered events from uncorrelated seismicity using the distribution of volumes of tetrahedra defined by closest neighbor events in the original and randomized seismic catalogs. The spatial disorder of the complex geometry of fault networks is then taken into account by defining faults as probabilistic anisotropic kernels. The structure of those kernels is motivated by properties of discontinuous tectonic deformation, and by previous empirical observations of the geometry of faults and of earthquake clusters at many spatial and temporal scales. Combining this a priori knowledge with information theoretical arguments, we propose the Gaussian mixture approach implemented in an Expectation-Maximization (EM) procedure. A cross-validation scheme is then used that allows the determination of the number of kernels which provides an optimal data clustering of the catalog. This three-steps approach is applied to a high quality catalog of relocated seismicity following the 1986 Mount Lewis (M_l=5.7) event in California. It reveals that events cluster along planar patches that are comparable to the size of the main event. The finite thickness of those clusters (about 290 m) suggests that events do not occur on well-defined and smooth euclidean fault core surfaces, but rather that there exist a deforming area and a damage zone surrounding faults which may be seismically active at depth. We propose a connection between our methodology and multi-scale spatial analysis, based on the derivation of a spatial fractal dimension of about 1.8 for the set of hypocenters in the Mount Lewis area, consistent with recent observations on relocated catalogs.

Second, we discuss a physically-based “multifractal stress activation" model of earthquake interaction and triggering based on two simple ingredients: (i) a seismic rupture results from thermally activated processes giving an exponential dependence on the local stress; (ii) the stress relaxation has a long memory. The interplay between these two physical processes are shown to lead to a multifractal organization of seismicity in the shape of a remarkable magnitude-dependence of the exponent p of the Omori law for aftershocks, which we observe quantitatively in real catalogs. The generalization of this research to other systems finds that multifractal scaling is a robust property of a large class of continuous stochastic processes, constructed as exponentials of long-memory processes.

Third, we formulate the problem of probabilistic predictions of global failure in the simplest possible model based on site percolation and on one of the simplest model of time-dependent rupture, a hierarchical fiber bundle model. We show that conditioning the predictions on the knowledge of the current degree of damage (occupancy density p or number and size of cracks) and on some information on the largest cluster improves significantly the prediction accuracy, in particular by allowing to identify those realizations which have anomalously low or large clusters (cracks). We quantify the prediction gains using two measures, the relative specific information gain (which is the variation of entropy obtained by adding new information) and the root-mean-square of the prediction errors over a large ensemble of realizations. For the hierarchical fiber bundle model, conditioning the measures of damage on the information of the location and size of the largest crack extends significantly the critical region and the prediction skills. These examples illustrate how on-going damage can be used as a revelation of both the realization-dependent pre-existing heterogeneity and the damage scenario undertaken by each specific sample. We then present a general prediction scheme of failure times based on updating continuously with time the probability for failure of the global system, conditioned on the information revealed on the pre-existing idiosyncratic realization of the system by the damage that has occurred until the present time. Its implementation on a simple prototype system of interacting elements with unknown random lifetimes undergoing irreversible damage until a global rupture occurs shows that the most probable predicted failure time (mode) may evolve non-monotonically with time as information is incorporated in the prediction scheme. In addition, both the mode, its standard deviation and, in fact, the full distribution of predicted failure times exhibit sensitive dependence on the realization of the system, similarly to “chaos" in other complex systems, providing a multi-dimensional dynamical explanation for the broad distribution of failure times observed in many empirical situations.

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DAMAGES AND FAILURE IN FIBER COMPOSITES WITH BRITTLE POLYCRYSTALLINE MATRICES

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Recent decades were characterized by intensive development of new fibrous composites with mineral matrices (oxides, borides, carbides, etc.) for medical applications (for instance, to replace biodegradable polymer composites for bones repair), for construction industry (fireproof parts of building, environment-proof parts of bridges, etc.), to enhance working temperature of structural materials for hot parts of machines, and so on. Typically the strengths of fibers (carbon, silicon carbide) are much higher (by two or more orders of magnitude) than the matrices ones. Besides, the matrices are highly defective and contain a large amount of cracks and pores. Thus it seems that the matrix damage and the fracture behavior have to crucially affect the mechanical response of these composite materials.

Mineral matrices are typically polycrystalline substances. The sizes, shapes, and orientations of the crystallographic axes of crystallites (grains) are usually random. So, the mineral matrices are heterogeneous materials consisted of anisotropic components with stochastic structure. Often mineral matrices consist of different types of crystallites, i.e. they are multicomponent materials itself. It seems obvious that failure of such complex media as the matrices in question can't be described by simple phenomenological fracture criteria like ultimate surface in stress space and so on. According to contemporary ideas of the mechanics of solids the failure of heterogeneous material is the result of a series of events which include damages nucleation, damaged areas growth, and eventually a final fracture of the material. In materials of stochastic structure these events are stochastic ones. The type of the final fracture state depends on the shape of loading path in a stress, strain, or displacement space. In other words the failure of complex heterogeneous material is a functional of loading path.

In this report we communicate the engineering micromechanical model of composites with ceramic polycrystalline matrices which quantitatively describes the nonlinear pseudo plastic behavior of the composites. The model is realized as computer algorithm which generates the constitutive relations for arbitrary loading path. The model doesn't use phenomenological adjusting parameters. All inputting information for the algorithm is well defined and available properties of single crystals the matrix grains consist of. The numerical results for simulation of few composites are presented; the comparison with experiment is made.

The work was supported by the Russian Foundation for Basic Research Grants 10-08-96062 and 11-08-96034.

EXPERIMENTAL RESEARCH OF HETEROGENEOUS STRAIN FIELDS AT DIFFERENT STAGES OF DEFORMATION USING DIGITAL IMAGE CORRELATION MEASUREMENT SYSTEM

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An actual problem of mechanics is experimental investigation of displacement and strain fields developing and evolution under inelastic deformation, especially during a plasticity zone, reference and developed postcritical deformation zones are forming. Heterogeneity of deformation process is presented practically on all observation scales. One of striking examples of spatial inhomogeneity of strain distribution is shoulder effect under tension of plastic materials. This process accompanies reduction of cross-section specimen. Issues of research heterogeneities of strain fields could be resolved with optical methods of deformable solid mechanics. There is a big number of different optical methods such as methods are based on photo-elastic effects, moiré fringe methods, holographic and laser speckle interferometry, shadow optical method of caustics, as well as digital image correlation (DIC). DIC is a computer-vision-based, non-contact, full-field surface strain measuring technique, which provides estimates of the displacement and strain fields by correlating a pair of digital images (before and after a deformation increment is applied) [1].

With the aim of analysis of mechanisms strain fields evolution on different stages of inelastic deformation and issues of experimental data processing when localization of plastic deformation visualizes was carried out mechanical testing. The uniaxial tension was carried out on cylindrical specimens with different length-to-diameter ratios. Material is steel 20. Experimental researches were conducted on the servohydraulic testing system Instron 8850 using 3D-digital image correlation measurement system Vic-3D Limess.

For each stage of deformation were experimentally carried out mean value of axial strain, which were determined at selected base in test portion of specimen by calculating of relative displacement of peripheral points, like technique of using noncontact video-extensometers. The evolution of axial strain on surface of specimen during yield drop is forming was researched. It was analyzed 5 areas of material.

Comparing the ‘stress-time’ curve for steel 20 under uniaxial tension and the ‘axial strain–time’ diagrams for selected areas of the cylindrical specimen at the stage of forming of yield drop the step-by-step involving of different areas of materials into deformation process was fixed. This effect can be named as ‘relay-race mechanism’ of deformation at the stage of yield drop forming. Under next loading at the stage of material hardening occurs restoration of symmetry in distribution axial strain, after that localization of deformation occurs in the central part of specimen. In turn at the postcritical stage was fixed elastic unloading of peripheral parts of specimen.

Accordingly with using digital image correlation the ‘relay-race mechanism’ of deformation at the stage of yield drop forming and effects of localization deformation in the central part were fixed and determined. On the stage of postcritical deformation elastic unloading of peripheral specimen parts were detected.

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CRYSTAL ELASTOVISCOPLASTIC THEORY USING ASYMMETRIC STRESS AND STRAIN MEASURES

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Correct description of the material's internal structure evolution and physical and mechanical properties which determined by its will enable the optimization of existing and developing new methods for obtaining materials with enhanced performance characteristics: submicrocrystalline, nanocrystalline, textured, capable of superplastic deformations materials.

The structure of a material multilevel constitutive model, based on the introduction of internal variables [1] is considered; example of its implementation for two levels is made. At the macro level Hooke's law in the velocity form is used, to determine the inelastic part of strain rate tensor and the tensor of effective elastic properties using statistical averaging. To describe the geometric nonlinearity (i.e. definition of the corotation derivative) at the macro level suggested an original approach based on the condition of matching the characteristics of stress-strain state at the macro and meso levels, while there is also a need to adjust of inelastic strain rate tensor. In the mesolevel model asymmetric measures of stress and strain state is used; as the constitutive relation we used asymmetric Hooke's law in the velocity form. In describing the polycrystalline aggregate's inelastic strain viscoplastic mechanisms intragranular dislocation slip (with the consideration of hardening due to different mechanisms), grain boundary sliding is accounted; describing the grains lattice orientations evolution is taking into account the incompatibility of slips in neighboring grains with the introduction of power factor - the couple stress tensor, based on which a criterion for the grains fragmentation from the interface is introduced.

Developed and implemented an algorithm to describe the polycrystalline behavior of an arbitrary loading. Examined some of the processes of material processing (draft, sediment constraint, equal-channel angular pressing), the simulation results (in particular, the texture) are well consistent with known experimental data.

This work was supported by RFBR (grants 10-08-96010-r_ural_a, 10-08-00156-a).

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THE PHYSICS AND SPD-TECHNIQUES TO PRODUCE BULK NANOSTRUCTURED METALLIC MATERIALS WITH UNIQUE PROPERTIES

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In recent years the development of bulk nanostructured materials has become one of the most topical directions in modern materials science. Nanostructuring of various metals and alloys paves the way to obtaining unusual properties that are very attractive for different applications [1]. In this research topic, the use of severe plastic deformation (SPD) techniques attracts special attention since it offers opportunities for developing new technologies of fabrication of various bulk semi-products in the form of sheets, rods, thin foils, wires for various specific applications. Especially significant progress in this area has been made in recent years when generation of new unique properties from nanostructuring has been demonstrated, such as very high strength and ductility, record-breaking fatigue endurance and superplasticity for a whole range of different metals and alloys [2,3]. An important scientific principle in properties enhancement is attributed to grain boundaries engineering in nanostructured materials. The innovation potential of this research area also becomes clear and the given talk discusses a number of such innovative developments. In particular, special emphasis is laid on the development of nanostructured metals and alloys for advanced engineering and functional applications.

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EXPERIMENTAL RESEARCH OF NON-LOCAL FAILURE CONDITIONS, STRAIN LOCALIZATION AND SCALE EFFECT ON POST-CRITICAL STAGE OF DEFORMATION

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In emergency situations, the most important property of materials is survivability. During the transition from the stage of equilibrium accumulation of damage to non-equilibrium stage of the destruction of the key role played the interaction of a deformed body with the loading system. As a result, depending on loading conditions, each point on the descending branch of stress-strain diagram can correspond to the time of the loss of bearing capacity resulting from a transition from stable to non-equilibrium stage of the process of accumulation of damage. Thus, the rigid loading system may contribute to the "adaptation" of the object in the process of destruction due to local dissipation of elastic energy.

The research is devoted to study of the materials behavior at the elastoplastic and postcritical deformation stages [1-4]. Problems of implementation of the postcritical stage deformation of materials during testing where considered. Dependence ultimate states of material of loading system stiffness were investigated by different experiments, such as a uniaxial tension of cylindrical solid specimens. Issues of limit states depending on the stiffness of the loading systems under uniaxial tension of solid cylindrical specimens experimentally were studied. The experimental researches, relating to finding a probably effects of resource plastic deformation increase for description of the behavior of materials in real operational influence environment. It is shown, that material deforms equilibrium up to destruction of a specimen into parts if loading system stiffness is sufficient. Investigate issues related to the possible presence of the scale effect under postcritical deformation stage [3].

The experiments, which are presented in this work, were performed in Center of Experimental Mechanics PSTU by the universal biaxial servohydraulic test system Instron 8850. The work was supported by Grant of the Russian Foundation for Basic Research RFBR-Ural (grant 08-08-00702) and Federal science and innovations agency in the network of the FTP "Researches and developments by priority directions of development scientific-technological complex of the Russian in 2007-2010" (government contract № 02.518.11.7135).

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AUTOWAVE MODEL OF PLASTIC FLOW

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Plastic flow localization was investigated on the micro- and macro-scale levels. Localization behavior was examined for a range of metals and alloys that differ in chemical bond and crystal lattice type (BCC, FCC, HCP, tetragonal and monoclinic), in structural state (single- or polycrystal, nanostructure, amorphous) and in deformation mechanism type (dislocation glide, twinning, martensitic transformation) [1-3]. It was established that deformation localization has the following regular features.

- Macro-scale plastic deformation tends to localize from microplasticity to viscous fracture stage.
- Four types of macro localization patterns are observed for yield plateau, linear and parabolic work hardening and prefracture stages.
- These patterns are regarded as different versions of self-excited wave generation.
- Significant variations in material structure and microstructure entail certain quantitative changes in localization patterns; however, their distinctive features remain intact.
- A correspondence rule is formulated, which holds that pattern type is determined by work hardening law acting at a given flow stage.

General regularities are discussed for plastic flow processes. On the base of this evidence a new plastic flow model is proposed the main assumption of which is that the regular features exhibited by the deformation behavior of a crystal are due to the interaction between its dislocation subsystem and acoustic emission pulses caused by dislocation shears.

It is shown that during material form changing, the deforming system would spontaneously separate into deforming volumes that alternate with those remaining undeformed at a given instant of time. Localization nuclei distributions tend to evolve in space and with time. Their evolution can be treated as self-organization manifested in terms of self-excited waves of different types generated in open systems. The separation of a medium into individual volumes and its self-organization involving interaction of its dislocation subsystem with acoustic emission impulses are of equivalent status. Moreover, the emergence of localized plasticity patterns is found to entail a decrease in the entropy of the deforming system. It is thus maintained that plastic flow macrolocalization can be addressed in the context of self-organization approach.

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