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MICROSTRUCTURE FORMATION IN THE FRAMEWORK OF THE NON-LOCAL THEORY OF INTERFACES

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Abstract. A new hydrodynamic theory based on non-equilibrium statistical mechanics is developed to describe the structure formation in dynamically deformed materials. Self-consistent non-local formulation of the boundary-value problem for a high-strain-rate process is reduced to a nonlinear operator set similar to some resonance problems. The branching of solutions to the problem determines both scales and types of the formed internal structure. A penetration problem for a long flat rigid plate into a viscous elastic medium is considered accounting for the dynamic structure formation following the high-rate straining in the framework of the nonlocal self-consistent approach. The obtained approximate analytical solution has shown to describe three regimes: initial, transient and quasi-stationary. It has been demonstrated that the mesoscopic structure formation had been initiated by relative accelerations in a medium localized near the plate surface moving at high velocity. The mesoscopic structures formed during the initial stage of penetration can affect the steady-state stage. It is very important that the proposed self-consistent theory allows taking into account the feed-back influence of the mesoscopic effects on macroscopic movement of the plate.

1. INTRODUCTION

According to the modern concepts in the physics of plasticity and strength, the physical processes responsible for the kinematic mechanisms of deformation vary in activation energy, typical scales, and time relaxation at different stages of straining. There exists a hierarchy of scale levels in a deformed solid where the certain kinematic mechanism is realized depending on strain-rate, boundary and initial conditions and non-linear properties of material [1]. In this connection it becomes clear that an adequate description of deformation should take into account the multiscale character of dynamic deformation and cannot be correct in terms of a single-level approach. For the last 15 years it has been found out that unlike the quasi-static straining the most important feature of the high-strain-rate processes in solids is the emergence of a space-time correlation among elementary carriers of deformation. The collective effects lead to a formation of new structure elements of larger scale compared to initial ones. These elements belong to the so-called mesoscopic scale level being intermediate between the atom-dislocation scale level and the macroscopic one. The mesoscopic structure elements begin to play a role of new carriers of deformation. A new branch of mechanics describing the deformation and fracture properties from the point of view of the multiscale hierarchy of carriers of deformation is called “mesomechanics” [1]. These are precisely the processes occuring at the mesoscopic level and properly described by mesomechanics are responsible for the macroscopic behaviour of solids. At present there is no satisfactory theory to describe the mesoscopic effects. Therefore, one needs an approach which being macroscopic could take into account the re-arrangement of the mesostructure in solids during dynamic straining.

It must be noticed that such a theory should be non-local both in space and in time and take into account the influence of the deformed volume as a whole including boundaries on the local deformation. Besides it should be self-consistent and involve a feedback allowing the reverse effect of the internal structure reformation on the macroscopic properties of a medium.

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2. SELF-CONSISTENT NON-LOCAL HYDRODYNAMIC APPROACH

Current results of non-equilibrium statistical mechanics show that the balance equations for macroscopic values are not entirely localized at highly non-equilibrium conditions [2,3]. They imply non-local in space and time constitutive relationships between macroscopic gradients G and dissipative fluxes P:

$$P(\boldsymbol{r},t) = P^{in}(\boldsymbol{r},t) + \int_0^t dt' \int_V d\boldsymbol{r}' \Re(\boldsymbol{r},\boldsymbol{r}',t,t';\varepsilon,\tau) \times G(\boldsymbol{r}',t'), \quad (1)$$

where weight factors $\Re(\boldsymbol{r},\boldsymbol{r}',t,t';\varepsilon,\tau)$ represent the relaxation transport kernels. In general, they are defined by unknown functionals of the macroscopic values and depend on space and time scale parameters ε,τ.

If a deviation from the local equilibrium is small, the scale parameters tend to zero: $\varepsilon,\tau\to 0$, the relaxation kernels reduce to the transport coefficients, and the relationships between gradients and fluxes become local and linear

$$P(\boldsymbol{r},t;\varepsilon,\tau) \xrightarrow[\varepsilon,\varsigma\to 0]{} \Re_0(\boldsymbol{r},t;\varepsilon,\tau) G(\boldsymbol{r},t) \equiv P_0(\boldsymbol{r},t),$$
$$\Re_0(\boldsymbol{r},t;\varepsilon,\tau) \equiv \int_0^t dt' \int_V d\boldsymbol{r}' \Re(\boldsymbol{r},\boldsymbol{r}',t,t';\varepsilon,\tau). \quad (2)$$

In this sense the scale parameters can be taken as being the non-locality and memory parameters.

The non-local hydrodynamic equations with memory are derived from the first principles [2,3]. A new trend of the non-local hydrodynamics developed by the author of this paper is a construction of self-consistent models of the relaxation transport kernels. Herewith, it is supposed that the boundary effects connecting the interaction of an open system with its surroundings, can be involved as an additional element of modeling for the relaxation transport kernels. The non-local models must correspond to general invariability and asymptotic principles and depend on a minimal quantity of parameters. Based on these principles a δ-type class of the relaxation transport kernels depending on parameters had been defined. The model parameters are connected with the influence of the internal structure on hydrodynamics as a whole. The physical sense of these parameters was examined by means of test problems for which it is possible to compare the results with those obtained in the kinetic theory and with experimental data [4].

It has been shown that a medium consisting of structure elements with finite linear size under inhomogeneous field of stresses becomes anisotropic, there exists spin motion due to an asymmetrical stress tensor [5]. This aspect of the approach has close connections with the theory of multipolar fluids. However, the proposed theory involves the spin properties of structure elements implicitly by means of the non-local reduced description that differs from the above-mentioned one. Generally, in the construction of non-local models with finite size space correlation one has take into account the polarization effects in a medium at highly non-equilibrium conditions.

According to the self-consistent approach to the construction of the model relaxation transport kernels, the model parameters are related to any integral properties of a system either through integral relationships including such characteristics as a flow rate, sum momentum, and energy, or by imposing additional boundary conditions [6-9]. These additional relationships for the model parameters complete a set of the non-local equations and make the formulation of the boundary problem self-consistent. The self-consistence of the proposed approach is its specific feature causing very important consequences.

The essential property of the proposed approach is preservation in the generalized hydrodynamic equations of the integral information about a system in the description of the local hydrodynamic fields. This circumstance in a radical way changes the concept of a boundary-value problem in the non-local theory. Unlike the classical continuum models, the self-consistent non-local models are uniformly valid up to boundaries. Thus, solutions of these equations can satisfy real boundary conditions considered as being the continuity condition for hydrodynamic fields. It means that one can use the non-slip condition even for high-rate flows on solid boundaries when classical continuum models result in discontinuities on boundaries or near them.

In as much as the additional boundary conditions making the self-consistent model closed can be imposed rather arbitrarily, this approach allows prediction of the conditions for formation of spatial structures with *a priori* predicted properties. This is very important advantage of the self-consistent non-local theory that may be used in a wide range of technological applications.

It was found that the self-consistent non-local formulation of boundary-value problems can be reduced by standard methods to a special type non-linear operator set which is typical to a wide range of resonance mechanical problems [10]. Due to the branching process arising in a non-linear system at non-equilibrium conditions the state of a system can change discontinuously as the conditions of external interaction change smoothly. It means that the proposed approach gives new possibilities to describe structure transitions. This approach due to its self-consistency, non-locality and non-linearity allows to describe a formation of internal structures in open non-equilibrium systems and applications in fluid mechanics, space engineering, chemical and micro-electronic technologies, synergetics and ecology.

3. NON-LOCAL GENERALIZED MODEL OF A VISCOUS ELASTIC AND PLASTIC MEDIUM WITH MESOSCOPIC STRUCTURES

In a one-dimensional case a total stress component in the x-direction σ_1 consists of spheric and deviatoric parts:

$$\sigma_1 = P + S_1. \tag{3}$$

The spheric component P of the normal stress σ_1 is assumed to take into account, besides the hydrostatic pressure, the effect of the velocity dispersion due to fluctuations of mesovolumes in velocity. As to the deviatoric stress tensor S_1, its determination is based on a solution of the so-called constitutive equation, its simplest form can be attributed to Maxwell:

$$\frac{\partial S_1}{\partial t} = \frac{4}{3}\mu\frac{\partial e_1}{\partial t} - \frac{S_1}{t_r(S_1)}, \tag{4}$$

where e_1 is the total (elastic plus plastic) deviatoric strain component, (4/3)μ denotes the elastic shear modulus and $t_r(S_1)$ the time of relaxation. If a medium has a well-defined critical shear stress $\tau^* = (3/4)S_1^*$, Eq. 4 should be rewritten in the form:

$$\frac{\partial S_1}{\partial t} = \frac{4}{3}\mu\frac{\partial e_1}{\partial t} - \frac{S_1 - S_1^*}{t_r(S_1)}. \tag{5}$$

This equation contains the plastic S_1^*, elastic μ and relaxation t_r characteristics of a medium. By integrating Eq. 5 in time we get:

$$S_1 = S_1^*\left[1 - \exp\left(-\int_0^t \frac{dt'}{t_r}\right)\right] - \frac{4}{3}\mu t_r$$
$$\times\int_0^t \frac{dt'}{t_r}\left[\exp\left(-\int_{t'}^t \frac{dt''}{t_r}\right)\right]\frac{\partial u}{\partial x}(x,t');$$
$$a)\quad S_1 \to S_1^* - \frac{2}{3}\eta\frac{\partial u}{\partial x};\quad \eta = 2\mu t_r \tag{6}$$
$$t_r \to \infty$$
$$b)\quad S_1 \to \frac{4}{3}\mu e_1$$
$$t_r \to 0.$$

Here $\eta = 2\mu t_r$ is an effective viscosity of a medium, and $\frac{\partial e_1}{\partial t}$ is substituted by $\frac{\partial u}{\partial x}$, where u is the mass velocity in the x direction. In case where the relaxation time tends to zero we have a viscous plastic medium, and as $t_r \to \infty$ a medium becomes elastic solid without any dissipative properties.

A new step resulted from the non-local hydrodynamic approach consists in the following representation of the relaxation stress [7]:

$$\frac{\partial S_1}{\partial t} + \frac{4}{3}\mu\frac{\partial u}{\partial x} = \frac{\partial S_1^*}{\partial t}, \tag{7}$$

$$S_1^r = S_1^{in}\int_0^t \boldsymbol{M}(0,t';t_r)dt' -$$
$$\frac{2}{3}\eta\int_0^t \frac{dt'}{t_r}M(t,t';t_r)\int_0^\infty \frac{dx'}{\varepsilon}\boldsymbol{N}(x,x';\varepsilon)\frac{\partial u}{\partial x'}. \tag{8}$$

The relaxation model (7) describes the most general time relaxation in accordance with the integral relaxation kernel $M(t,t';t_r)$ (or a memory function) which becomes of simple exponent type only near the limit $t_r \to 0$. Besides the time relaxation, Eq. 7 contains the space relaxation due to the new internal structure formation in accordance with the integral relaxation kernel $\boldsymbol{N}(x,x',\varepsilon)$ which introduces the non-local properties of a medium inside a given volume under imposed boundary conditions far from equilibrium.

By integrating Eqs. 7 and 8 we have a more general model than the Maxwell one given by Eq. 6:

$$S_1 = \frac{4}{3}\mu e_1 + S_1^{in}\int \boldsymbol{M}(0,t';t_r)dt' -$$

$$\frac{2}{3}\eta\int_0^t \frac{dt'}{t_r} M(t,t';t_r)\int_0^\infty \frac{dx'}{\varepsilon}\boldsymbol{N}(x,x';\varepsilon)\frac{\partial u}{\partial x'}. \qquad (9)$$

In case when the memory function has a simple exponent form $\boldsymbol{M}(t,t';t_r) = \exp\left(-\int_{t'}^{t}\frac{dt'}{t_r}\right)$ or $\exp\left(-\frac{t-t'}{t_r}\right)$ for $t_r = const$ and $\varepsilon \to 0$, $\boldsymbol{N}(x,x';\varepsilon) \to \delta(x-x')$ we have got Eq. 6 with $S_1^{in} = S_1^*$. It means that without taking into account a formation of internal structure we have artificially to introduce the consequence of the structure reformation as additional initial conditions. As a matter of fact, S_1^* is a result of a relaxation both in space and time which is already completed for the time $t_r^* << t_r$.

So, we can state that the relaxation model (7) and (8) is the most general model including the relaxation both in time and in space followed by the structure formation. Its particular case is the well-known Maxwell relaxation model for elastic-viscous-plastic medium.

If the relaxation parameters t_r and ε are rather small, the space and time relaxation effects can be considered separately. Since the internal structure formation of the mesoscopic scale level are of the most interest for us, we can neglect the time relaxation and consider only the space relaxation supposing $t_r \to 0$. In accordance with the new approach, the non-local generalization for the well-known Maxwell model of a medium has been obtained [6]. It contains the space relaxation integral kernel $N(x,x';\varepsilon) = (1+\alpha)\exp\left[-\frac{\pi}{\varepsilon^2}(x'-x-y)^2\right]$. Then instead of Eq. 8 we have a constitutive equation

$$S_t = \frac{4}{3}\mu e_1 - \frac{2}{3}\eta(1+\alpha)\times$$

$$\int_0^\infty \frac{dx'}{\varepsilon}\exp\left[-\frac{\pi}{\varepsilon^2}(x'-x-y)^2\right]\frac{\partial u}{\partial x'}(x',t). \qquad (10)$$

The non-local model includes three internal parameters $\alpha, \gamma, \varepsilon$ having the following physical sense:

1) $(1+\alpha)$ is the relative effective viscosity of a medium, correcting the value of viscosity η for a case of medium with internal structure.
2) γ is the polarization parameter along a largest gradient direction due to boundary conditions; there is a close connection between and existence of rotations of internal structure elements [6-9].
3) ε is the typical radius of non-local correlation or a typical relaxation length connected with a typical scale of internal structure element.

All the model parameters are unknown functionals of macroscopic gradients [3]. In order to determine the parameters, we should use three functional relationships derived from non-equilibrium boundary conditions and additional information concerning the macroscopic reaction of a system on the loading conditions.

4. NON-EQUILIBRIUM DISTRIBUTION FUNCTION OF MEDIUM ELEMENTS ON THE MESOSCOPIC SCALE LEVEL

From the point of view of the kinetic theory the problem of high-rate processes is reduced to the definition of a nonequilibrium distribution function of medium elements in velocities. According to the modern results of the non-equilibrium statistical mechanics, a non-equilibrium distribution function consists of two parts [3]. Quasi-equilibrium part generalizes the well-known local-equilibrium distribution function in case of non-equilibrium conditions and contains only the first moments of the distribution. The high-order moments are determined by its essentially non-equilibrium part. Instead of the thermodynamic temperature, at non-equilibrium conditions one should use the mean velocity dispersion

$$D = \sqrt{\frac{D_1^2 + D_2^2 + D_3^2}{3}}, \quad D_i = \left\langle \nu_i^2 - \left\langle \nu_i \right\rangle^2 \right\rangle,$$

where D_i is the mean-square value of the velocity dispersion in the i-direction due to the velocity fluctuations of the mesoscopic scale level. The components $D_i(\boldsymbol{r},t)$ along different directions can be different, because of the anisotropic properties of a non-equilibrium system. Besides, as mesoscopic scales can change rapidly, the medium element mass changes also. That is why instead of the distribution in velocities it is necessary to introduce a distribution in impulses of mesoelements. Then quasi-equilibrium distribution function in impulses for medium elements on the mesoscopic scale level takes form:

$$f_0(\vec{p},\vec{r},t) = p\frac{(\pi\rho(\vec{r},t))^{-3/2}}{\sqrt{D_1 D_2 D_3}}\times$$

$$\exp\left\{-\sum_{i=1}^{3}\frac{(p_i - \rho\nu_i(\vec{r},t))^2}{pD_i(\vec{r},t)}\right\}. \qquad (11)$$

The distribution function (11) describes reversible transport processes occuring, however, at non-equilibrium conditions. Quasi-equilibrium distribution implies that thermodynamic relationships of the classical equilibrium thermodynamics take place at non-equilibrium conditions, but the concepts of temperature and pressure loose their classical thermodynamic sense.

In order to describe dissipative processes a non-equilibrium distribution function in explicit form has been derived in paper [11]:

$$f(\vec{p},\vec{r},t) = f_0\left[1+\frac{A}{\mu}p_ip_jP_{ij}^{in} - \frac{B}{\kappa}(1-Cp^2)p_iq_i^{in}\right] + \int_0^t dt'\int_V d\vec{r}\,' f_0\left[1+\frac{A}{\mu}\Re_{ij}(\vec{r},\vec{r}\,',t,t')P_{ij}^{NS}(\vec{r}\,',t')p_ip_j - \frac{B}{\kappa}(1-Cp^2)\Re_{ij}(\vec{r},\vec{r}\,',t,t')q_i^{NS}(\vec{r}\,',t')p_i\right]. \quad (12)$$

The function (12) generalizes the well-known distribution function in the Navier-Stokes approximation for high-rate processes. The viscous stress tensor and diffusive energy flux calculated using the distribution (12) correspond to non-linear, non-local and retarding relationships between dissipative fluxes and thermodynamic forces (1) derived in the framework of the non-equilibrium statistical thermodynamics.

The first term in expression (12) describes a decaying process of initial correlations. The second one represents an averaged both in space and time with integral kernels, $\Re_{ij}$, and $\Re_i$, Navier-Stokes distribution function. The obtained distribution function incorporates history of a process, geometry of a system and depends on a set of boundary and integral conditions imposed on a system.

5. NON-EQUILIBRIUM DISTRIBUTION FUNCTION FOR SHEAR FLOWS

For example, consider non-stationary shear flow of viscous fluid at a constant thermodynamic temperature near a thin plate in a plane y=0, driven into a motion at the time t=0 with a finite acceleration $w(t)$ in the x-direction. The distribution function (12) for this problem takes the form [11]

$$f(\vec{p},y,t) = f_0\left[1+Ap_xp_y(1+\alpha)\int_0^\infty\frac{dy}{\varepsilon}\times\exp\left(-\frac{\pi}{\varepsilon^2}(y'-y-\gamma\right)^2\frac{\partial u}{\partial y}(y',t)\right]. \quad (13)$$

As the shear component of the transport kernel $\Re(y,y',t)$ a model expression takes into account only non-local effects normal to the plate without memory effects. The x-component of the mass velocity $v_x \equiv u(y,t)$ involved in the function, satisfies the following equation:

$$\frac{\partial u}{\partial t} = \nu(1+\alpha)\frac{\partial}{\partial y}\int_0^\infty\frac{dy'}{\varepsilon}\times \exp\left(-\frac{\pi}{\varepsilon^2}(y'-y-\gamma)^2\right)\frac{\partial u}{\partial y'}(y',t), \quad (14)$$

where ν is the effective kinematic medium viscosity.

In case under consideration only one component of the mesoelement spin is not zero, $s_z \neq 0$. It satisfies the balance equation:

$$\rho\frac{\partial s_z}{\partial t} + \frac{\partial}{\partial y}\Pi_{xy} = I, \quad (15)$$

where Π_{xy} is the shear component of the vortical stress tensor, and the source in the right-hand part is defined by the polarization parameter γ:

$$I = P_{yx} - P_{xy} = -\mu(1+\alpha)\int_0^\infty\frac{dy'}{\varepsilon}\times\left[\exp\left(-\frac{\pi}{\varepsilon^2}(y'-y-\gamma)^2\right) - \exp\left(-\frac{\pi}{\varepsilon^2}(y'-y)^2\right)\right]\frac{\partial u}{\partial y'}\xrightarrow[\gamma\to 0]{} 0. \quad (16)$$

The parameter γ shows to make a medium model anisotropic. However, the Eqs. 15 and 16 are not necessary to determine the polarization parameter γ.

If the local friction on a plate is assumed to be known, one can use the following equation:

$$P_{xy}(0,t) = -\nu(1+\alpha)\int_0^\infty\frac{dy'}{\varepsilon}\exp\left(-\frac{\pi}{\varepsilon^2}(y'-\gamma)^2\right)\frac{\partial u}{\partial y'}, \quad (17)$$

and require the acceleration field to be continuous on the interface of a plate

$$w(t) = \nu(1+\alpha)\int_0^\infty\frac{dy'}{\varepsilon}\frac{2\pi}{\varepsilon}(y'-\gamma)\exp\left(-\frac{\pi}{\varepsilon^2}(y'-\gamma)^2\right)\frac{\partial u}{\partial y'}. \quad (18)$$

Eqs. 17 and 18 determine the parameters $\alpha(t)$, $\gamma(t)$ as the time depending functions. All together with the Eq. 14 they make the problem about the distribution function for shear flows closed up to the scale parameter e considered to be external in this formulation.

6. EXPERIMENTAL BASIS OF THE NON-LOCAL APPROACH

Steady-state hydrodynamic theory has been applied to penetration problems since the 1940th. It is generally believed that hydrodynamic theory is applicable when penetration pressures are much greater than the target flow stress. Experimental data, however, show penetration velocities and instantaneous penetration efficiencies fall below that expected from hydrodynamic theory even at very high impact velocities. Accounting for mechanical properties of materials such as strength, compressibility and viscosity is yet unable to explain all experimental data [12]. The main reason for the theory and experiments discrepancy seems to be a contradiction between phenomenological models of penetration and non-equilibrium thermodynamics of open systems. The phenomenological models cannot take into account the self-organization of open systems far from equilibrium by means of a formation of dissipative structures. During the high-velocity interaction of the penetrator-target couple which certainly is viewed to consist of two open systems, a change of the kinematical mechanism of straining can occur under certain strain-rate conditions. Under impact velocity about 350 m/s the spall strength of a material increases in a step-like manner. Microstructure investigations of specimens after shock tests reveal the transition from translational mechanism of deformation to a rotational one. Instead of shear banding on the mesoscopic scale level (0.1-10μm), numerous rotational cells of the same scale level have been found. Investigations of the propagation of elastic-plastic waves fulfilled by Yu. I. Mescheryakov [13,14] demonstrate chains of rotational cells (vortexes)in copper target loaded under uniaxial strain conditions with the impact velocity of 160 m/s. Element analysis of inner structure of rotational cells shows them being consisted of the same material as a matrix. It means that the cells represent the vortexes formation frozen in material itself (not inclusions). One of the remarkable features of these chains is that, being elongated in the wave propagation direction, they cross grain boundaries without changing of their direction. It means that during the plastic front passage is in an unstable state, and material moves non-uniformly like numerous microflows. For the microflows, grain boundaries disappear as strong obstacles. Narrow region between adjacent microflows at different velocities transform either into shear band or rotational (vortex) chain depending on an interaction on the mesoscopic scale level. An analogous situation is known to appear at interfaces between two layers in liquids, that is, the so-called “cat-eyes” formations in the Helmholtz instability phenomenon. It has been also found out [13,14] that the cross-section of rotational cells along a chain are changed in a non-monotonous way. Their size has two maxima with gradual decreasing to edges and in the middle of a chain. Sometimes, instead of rotations in the middle of a chain there is a short shear band. Comparison of the maximum positions with the time resolved profile of mass acceleration allows to conclude that they are closely correlated. At the same time, shear banding occurs when acceleration changes its sign and simultaneously the mass velocity dispersion is maximum. With this experimental data it has been concluded that the difference in accelerations of microflows is responsible for the rotational mechanism of deformation, while the difference in velocities is responsible for shear banding.

Although the liquid-like behaviour of a medium has been found out in a shock compressed solid, this phenomenon can not be described in the framework of traditional elastic-plastic theory. On the other hand, it also cannot be described using classical hydrodynamics of either an ideal liquid or a viscous newtonian one. Navier-Stokes equations are valid for laminar flows of structureless media, but they can not provide a transition from laminar to turbulent flows.

So, in order to theoretically describe a transition from shear banding to rotational cells during shock wave propagation processes or in case of high-velocity penetration, it is necessary to take into account the dynamic structure formation including rearrangements of structure scales and changing of kinematic mechanisms of deformation. That is why the theory in question should be hydrodynamic liquid-like behaviour), non-local (collective interaction, dependence on boundary conditions of internal structure scales) and self-consistent (with a feedback). In the following, one can see that the proposed non-local self-consistent approach satisfies all the required conditions.

7. NON-LOCAL PENETRATION MODEL WITH INTERNAL STRUCTURE EFFECTS

Formulation of a problem. A penetration problem for an infinite flat plate into a viscous medium is considered accounting for the dynamical structure formation following a high-rate straining. A plate of a finite thickness l has a constant density r_1. The initial penetration velocity $U(0)=U_0$. The velocity vector is directed along the x-axis on the surface of the plate and the y-axis is normal to the plate. The one-dimensional formulation is modeling of a movement of a large plate in a medium with the edge effects being neglected and allows determining a friction on the side surfaces of a plate. Here we choose the plane geometry, because of its simplicity allowing to obtain solutions in an explicit form and because of its correspondence to the same plane geometry of the shock wave loading experiments. Further we shall show that, for the formulated problem, it is possible to use the experimentally measured values of the shock wave propagation characteristics for the plane penetration.

A motion of a plate element of a unit area moving along the x-axis with a velocity $U(t)$ and the acceleration $W(t)$ under the action of a medium resistance $-2P_{xy}(0,t)$ is governed by the following equation:

$$\rho_1 l W(t) = -2P_{xy}(0,t) \le 0, \tag{19}$$

where $W(t)$ is the plate deceleration and $P_{xy}(0,t)$ is the local friction on the side surface of a plate. Eq. 19 contains a lateral resistance and does not involve a frontal one.

In the scope of the self-consistent non-local approach, equations of the medium motion with accounting for the internal structure effects has a form

$$\rho_0 \frac{\partial u}{\partial t} + \frac{\partial P_{xy}}{\partial y} = 0;$$

$$\frac{\partial P_{xy}}{\partial t} + G\frac{\partial u}{\partial y} = -\frac{\partial}{\partial t}\left\{\rho_0 \nu \int_0^\infty \frac{dy'}{\varepsilon}\frac{2\pi}{\varepsilon^2}(y'-y-\gamma)\exp\left(-\frac{\pi}{\varepsilon^2}(y'-y-\gamma)^2\right)\frac{\partial u}{\partial y'}\right\}. \tag{20}$$

Internal model parameters in the non-local model (20), that is, parameters $\nu(t)$, $\varepsilon(t)$, $\gamma(t)$ having the definite physical sense and representing the dynamic structure formation should be determined by boundary conditions in a self-consistent way with a feed-back.

Functional relationships determining the model parameters are given by Eq. 19 connecting the local friction with the plate deceleration

$$-\rho_1 l W(t) = -G\int_0^t dt \frac{\partial u}{\partial y} - \rho_0 \nu \times \int_0^\infty \frac{dy'}{\varepsilon}\exp\left(-\frac{\pi}{\varepsilon^2}(y'-\gamma)^2\right)\frac{\partial u}{\partial y'}; \tag{21}$$

and by Eq. 20 at y=0, presenting the discontinuity condition on the plate surface for the acceleration field, besides that for the velocity one:

$$\rho_0 W(t) = -G\int_0^t dt \frac{\partial^2 u}{\partial y^2} - \rho_0 \nu \times \int_0^\infty \frac{dy'}{\varepsilon}\frac{2\pi}{\varepsilon^2}(y'-\gamma)\exp\left(-\frac{\pi}{\varepsilon^2}(y'-\gamma)^2\right). \tag{22}$$

Functional relationships 21 and 22 determine only two of the three model parameters. In order to determine the third one, an extra relationship is needed.

Let us use an integral balance equation for the internal energy of a system in a whole without heat conduction.

$$\int_0^\infty \frac{\partial E}{\partial t}dy + \int_0^\infty P_{xy}(y,t)\frac{\partial u}{\partial y}(y,t)dy = 0. \tag{23}$$

By using an analogy with the thermodynamic equation connecting an internal energy with a temperature near the local equilibrium, let us introduce the macroscopic velocity dispersion D playing the role of a temperature in non-equilibrium processes:

$$\frac{\partial E}{\partial t} = \rho_0 c_m \frac{\partial D}{\partial t}, \tag{24}$$

where the notation $c_m = \left(\frac{\partial E}{\partial D}\right)$ is introduced for the energy capacity of different scale fluctuations initiated by non-equilibrium transport processes. At the constant temperatures without the heat conduction, the value c_m characterizes only the large-scale fluctuations at the mesoscopic scale level. Formulae 23 and 24 show that at $c_m \to 0$ mesofluctuations are not excited, and the total macroscopic energy transfers immediately to the heat through the viscous friction. At finite values c_m a part of the macroscopic kinetic energy transfers to the mesoscopic scale level where the mesofluctuations excite and form new internal structures. At $c_m \to \infty$ mesofluctuations are frozen; no energy exchange between scale levels occurs.

So, as a result, we have a closed formulation of the conjugate problem: plate motion Eq. 19, medium motion Eq. 20 and three functional relationships with respect to the three model parameters $\nu(t)$, $\varepsilon(t)$, $\gamma(t)$ determining the medium internal structure properties such as an effective viscosity, structure element sizes, structure element rotations (medium polarization) (19)-(21), (22), (23)-(24). Herewith a medium reaction to the plate movement is assumed to be known: $U(t)$ is the plate velocity, $Q(t) = \rho_0 \int_0^\infty u(y,t)dy$ is the flow rate of a medium through a section normal to the plate ($\delta Q/\delta t = P_{xy}(0,t)$), $D(t)$ is the velocity dispersion in a medium. The dynamic balance of these values characterizes, on the one hand, an energy and momentum exchange between the plate and medium motions on the macroscopic scale level, and, on the other hand, the structure formation on the mesoscopic scale level.

So, the obtained formulation of the problem allows to reconstruct of the internal structure dynamics on the base of the macroscopic medium reaction. As far as functional relationships are essentially nonlinear with respect to the parameters $\varepsilon(t)$, $\gamma(t)$, they are defined in a non-unique way. This is a specific feature of non-equilibrium processes followed by multi-scale dynamic structure formation. On the other hand, by means of the obtained formulation (21)-(24), with the internal structure dynamics known we can define the plate and medium dynamics in a correct way accounting for the internal structure effects.

Solution of the problem in the first approximation. When the internal structure parameters are small and can be neglected, that is, $\nu(t)$, $\varepsilon(t)$, $\gamma(t) \to 0$, and the plate is driven into a motion instantaneously up to a constant velocity U_0 which is sufficiently high to omit elastic properties of a medium: $W(t) \to U_0\delta(t)$, Eq. 20 takes the following form of conventional diffusion equation:

$$\frac{\partial u}{\partial t} = \nu \frac{\partial^2 u}{\partial y^2}. \tag{25}$$

The solution of Eq. 25 under the given initial and boundary conditions ($u(y=0,t)=0$ and $u(y\to\infty,t)\to 0$, respectively) is well-known to be as follows:

$$u^0(y,t) = U_0\left(1 - \operatorname{erf}\frac{y}{2\sqrt{\nu t}}\right),$$

$$P_{xy}(y,t) = -\rho_0 \nu \frac{\partial u}{\partial y} = \rho_0 \nu \frac{U_0}{\sqrt{\pi \nu t}} \exp\left(-\frac{y^2}{4\nu t}\right).$$

All the attempts to generalize this solution to a case of non-stationary motion of a plate lead inevitably to a new physical object: thin dynamic near-boundary layer existing for all real media motions at high velocities (Knudsen layers in gases, laminar boundaries in turbulent flows, molecular layers in micropolar fluids). Without accounting these layers formed by the internal structure medium elements the hydrodynamic fields become discontinuous on boundary surfaces. That is why for strucureless medium at high velocities the hydrodynamic profiles should have discontinuities on the plate surface.

Now let us consider the plate penetration into a medium initially being at rest. Then a medium is retarding from the plate and a slip velocity appears with respect to the plate $\Delta u(t)$ introduced instead of the flow rate $Q(t)$ as a new fundamental macroscopic characteristic of a medium reaction to a non-stationary disturbance:

$$U^0(y,t) = (U - \Delta u)(t)\left(1 - \operatorname{erf}\frac{y}{2\sqrt{\nu t}}\right) + \Delta u(t)(1 - \theta(y)). \tag{26}$$

The velocity profile for the structured medium is supposed to consist of two parts: quasi-stationary profile generalizing the case of steady-state movement of the plate to the non-stationary one in structured medium, and dynamic boundary layer formed due to an interaction between the boundary surface and the medium structure elements. The introduction of a dynamic layer allows satisfying the non-slip boundary condition on the plate during all stages of its motion.

From Eq. 26 we have the following expression for the velocity gradient in the 0th approximation:

$$\frac{\partial u^0}{\partial y} = -\frac{U - \Delta u}{\sqrt{\pi \nu t}} \exp\left(-\frac{y^2}{4\nu t}\right) - \Delta u(t)\delta(y). \tag{27}$$

Now using the iteration procedure developed for the special type non-linear operator sets (see the first part of this paper). Substituting the gradient (27) into the integrals in formulae (19)-(23) we have got the following expressions for the shear component of the viscous stress tensor and the acceleration field in a medium in the 1st approximation:

$$P_{xy}(y,t)=\rho_0\nu\left[\frac{U-\Delta u}{\sqrt{\pi\nu t}}\int_0^\infty\frac{dy'}{\varepsilon}\exp\left(-\frac{\pi}{\varepsilon^2}(y'-y-\gamma)^2-\frac{y'^2}{4\nu t}\right)+\frac{\Delta u(t)}{\varepsilon}\exp\left(-\frac{\pi(y+\gamma)^2}{\varepsilon^2}\right)\right]; \quad (28)$$

$$\frac{\partial u}{\partial t}(y,t)=\nu\frac{U-\Delta u}{\sqrt{\pi\nu t}}\int_0^\infty\frac{dy}{\varepsilon}\exp\left(-\frac{\pi}{\varepsilon^2}(y'-y-\gamma)^2-\frac{y'^2}{4\nu t}\right)+\frac{\Delta u(t)}{\varepsilon}\frac{2\pi(y+\gamma)}{\varepsilon^2}\exp\left(-\frac{\pi(y+\gamma)^2}{\varepsilon^2}\right)\Bigg]. \quad (29)$$

The first terms on the r.h.s. of Eqs. 28 and 29 represent the quasi-stationary parts of the shear stress and acceleration profiles, respectively, and the second ones take into account the dynamic layer effects.

Though the friction on the plate is always positive, Eq. 18 shows that in general case an acceleration in a medium can change its sign: it is negative in the dynamic layer, and it is positive on the plate and outside of the layer.

$$\int_0^\infty\frac{dy'}{\varepsilon}\frac{2\pi}{\varepsilon^2}(y+\gamma-y')\exp\left(-\frac{\pi}{\varepsilon^2}(y'-y-\gamma)^2-\frac{y'^2}{4\nu t}\right)=$$
$$\int_0^{y+\gamma}\frac{dy'}{\varepsilon}\frac{2\pi}{\varepsilon^2}(y+\gamma-y')\exp\left(-\frac{\pi}{\varepsilon^2}(y'-y-\gamma)^2-\frac{y'^2}{4\nu t}\right) \quad (30)$$
$$-\int_0^\infty\frac{dy'}{\varepsilon}\frac{2\pi}{\varepsilon^2}(y'-y-\gamma)\exp\left(-\frac{\pi}{\varepsilon^2}(y'-y-\gamma)^2-\frac{y'^2}{4\nu t}\right);$$

Actually, a sign of the integral on the l.h.s. of (30) is defined by a difference of two positive integrals on the r.h.s. of (30). It means that, if the integrals cancel each other, shear bands can arise on the external boundary of the dynamic layer. On the contrary, rotations in the layer boundary disappear. From (28) and (29) the following values for the local friction on the plate and the plate deceleration are obtained:

$$P_{xy}(0,t)=\rho_0\nu\left[\frac{U-\Delta u}{\sqrt{\pi\nu t}}\int_0^\infty\frac{dy'}{\varepsilon}\exp\left(-\frac{\pi}{\varepsilon^2}(y'-\gamma)^2-\frac{y'^2}{4\nu t}\right)+\frac{\Delta u(t)}{\varepsilon}\exp\left(-\frac{\pi\gamma^2}{\varepsilon^2}\right)\right]; \quad (31)$$

$$W(t)=\nu\left[\frac{U-\Delta u}{\sqrt{\pi\nu t}}\int_0^\infty\frac{dy'}{\varepsilon}\frac{2\pi}{\varepsilon^2}(\gamma-y')\exp\left(-\frac{\pi}{\varepsilon^2}(y'-\gamma)^2-\frac{y'^2}{4\nu t}\right)+\frac{\Delta u(t)}{\varepsilon}\exp\left(-\frac{\pi\gamma^2}{\varepsilon^2}\right)\right]. \quad (32)$$

It should be noted that the dynamic layer effect on the friction and deceleration is positive. The correlation between the internal structure effects and the system dynamics is essential: without accounting for the internal structure, that is, in case of $\nu(t)$, $\varepsilon(t)$, $\gamma(t)\to 0$, instead of Eq. 26, we have got a steady-state motion of the plate in continuum medium with $W(t)\to 0$. However, the internal structure effects cause even a steady-state movement of the plate at high velocities, but the medium structure does not change in time and characterized by constant values of the parameters ν, ε, γ and the slip velocity $\Delta u(t)$.

So, accounting for the internal structure effects, it is possible even in the 1st approximation to describe non-stationary motion of a system in a correct way including the initial medium acceleration stage of a process, a steady-state stage and the plate deceleration final stage.

Analysis of the obtained solution. Now let us consider an explicit form of the functional relationships (31) and (32) for the local friction on the plate and the plate acceleration

$$P_{xy}(0,t)=\rho_0\nu\left[\frac{U-\Delta u}{\sqrt{\pi\nu t}}\frac{l_0(0,\varepsilon,\gamma)}{\beta}\exp\left(-\frac{\gamma^2}{4\nu t\beta^2}\right)+\frac{\Delta u(t)}{\varepsilon}\exp\left(-\frac{\pi\gamma^2}{\varepsilon}\right)\right]; \quad (33)$$

$$W(t)=\nu\left[\frac{U-\Delta u}{\sqrt{\pi\nu t}}\frac{1}{\varepsilon\beta^2}\exp\left(-\frac{\pi\gamma^2}{\varepsilon^2}\right)\times\left[1-\frac{l_0(0,\varepsilon,\gamma)}{\beta}\frac{\varepsilon\gamma}{2\nu}\exp\left(\frac{\pi\gamma^2}{\varepsilon^2\beta^2}\right)\right]+\frac{\Delta u(t)}{\varepsilon}\frac{2\pi\gamma}{\varepsilon^2}\exp\left(-\frac{\pi\gamma^2}{\varepsilon}\right)\right]; \quad (34)$$

where the following notations are accepted:

$$\beta=\sqrt{1+\frac{\varepsilon^2}{4\pi\nu t}};$$

$$l_0(y,\varepsilon,\gamma)=\frac{1}{2}\left(1+erf\,\frac{\sqrt{\pi}(y+\gamma)}{\varepsilon\beta}\right).$$

The energy equation (23) with accounting for the Eq. 24 and after substituting the 0-order velocity gradient (27) takes the form

$$\rho_0 c_m \frac{\partial}{\partial t}\int_0^\infty D(y,t)dt + \rho_0 \nu \frac{U-\Delta u}{\sqrt{\pi\nu t}}\left[\frac{2A_1(U-\Delta u)}{\sqrt{1+\beta^2}} - \frac{A_2 \Delta U}{\beta}\right] + (\rho_1 l W - l f)(t)\Delta u = 0, \qquad (35)$$

where the integrals are denoted as follows

$$A_1 = \int_0^\infty dy \frac{l_0(0,\varepsilon,\gamma)}{\beta}\exp\left(-\frac{(y+\gamma)^2}{4\nu t\beta^2} - \frac{y^2}{4\nu t}\right);$$

$$A_2 = \int_0^\infty dy \exp\left(-\frac{(y+\gamma)^2}{4\nu t\beta^2} - \frac{y^2}{4\nu t}\right).$$

The first term on the r.h.s. of Eq. 35 represents the rate of kinetic energy evolution on the mesoscopic scale level (energy of mesofluctuations), the second one corresponds to a work of friction, and the third term describes an energy influence of the dynamic layer near the plate surface.

Let us separate a part of friction corresponding to the structureless medium in Eq. 33

$$P_{xy}(0,t) = P_{xy}^0(0,t)\frac{l_0(0,\varepsilon,\gamma)}{\beta}\exp\left(-\frac{\gamma^2}{4\nu t\beta^2}\right) + \rho_0 \nu \frac{\Delta u(t)}{\varepsilon}\left[\exp\left(-\frac{\pi\gamma^2}{\varepsilon^2}\right) - \frac{\varepsilon}{\sqrt{\pi\nu t}}\frac{l_0(0,\varepsilon,\gamma)}{\beta}\exp\left(-\frac{\gamma^2}{4\nu t\beta^2}\right)\right]. \qquad (36)$$

Consider the friction in structured medium at the steady-state stage of penetration that takes place at rather large time $t\to\infty$, when the acceleration can be neglected, that is, $W(t)\to 0$:

$$P_{xy}(0,t) = P_{xy}^0(0,t) l_0(0,\varepsilon_\infty,\gamma_\infty) + \rho_0 \nu_\infty \frac{\Delta u_\infty}{\varepsilon_\infty}\left[\exp\left(-\frac{\pi\gamma_\infty^2}{\varepsilon_\infty^2}\right) - \frac{\varepsilon_\infty}{\sqrt{\pi\nu_\infty t}}\frac{l_0(0,\varepsilon,\gamma)}{1}\right] \to P_{xy}^0(0,t) - \rho_0 \nu_\infty \frac{\Delta u_\infty}{\sqrt{\pi\nu_\infty t}}. \qquad (37)$$

Eq. 37 shows that in general the local friction is determined by constant values of the internal structure parameters ν_∞, ε_∞, γ_∞, and also by the constant slip velocity Δu_∞. The friction takes its classical value $P_{xy}^0(0,t)$ only for the structureless medium and without a slip.

At the initial stage of penetration as $t\to 0$,

$$P_{xy}(0,t) \to \rho_0 \nu_0 \frac{\Delta u_0}{\varepsilon_0}\exp\left(-\frac{\pi\gamma_0^2}{\varepsilon_0^2}\right) = \rho_0 \nu_0 \frac{U_0}{\varepsilon_0}\exp\left(-\frac{\pi\gamma_0^2}{\varepsilon_0^2}\right). \qquad (38)$$

At the initial stage the friction is entirely determined by the medium internal structure and the slip velocity corresponding to the initial penetration velocity. It should be noted that at the very initial moment of time ($t\to 0$) the friction value is finite. In the limiting case where $\varepsilon\to\infty$, if a medium has not been deformed initially and can be considered as a solid, the viscous friction vanishes at all.

The plate acceleration at the initial stage is also closely connected with the medium structure:

$$W(t) \to \nu_0 \frac{\Delta u_0}{\varepsilon_0}\frac{2\pi\gamma_0}{\varepsilon_0^2}\exp\left(-\frac{\pi\gamma_0^2}{\varepsilon_0^2}\right). \qquad (39)$$

In transition regimes at finite times and finite medium structure parameters dynamic structure formation plays the key role. Depending on the initial medium structure, initial penetration velocity and a system geometry the friction effect can be either essentially increased and decreased. It must be underlined that all the effects occur only at high rates in regions where gradients are large with the state of a system being far from equilibrium.

So, macroscopic penetration characteristics $U(t)$, $\Delta u(t)$, $D(t)$ can be calculated on the base of the proposed approach using the governing relationships (33)-(35) with the structure dynamic characteristics known. On the contrary, if the macroscopic functions $U(t)$, $\Delta u(t)$, $D(t)$ are measured, relationships (33)-(35) govern the internal structure parameters $\nu(t)$, $\varepsilon(t)$, $\gamma(t)$ reconstructing the structure formation dynamics induced by high-rate macroscopic motion in a system.

Similarity penetration criteria. Let us rewrite Eqs. 33-35 in a non-dimensional form, supposing U_0, D^*, t^*, ν^*, ε^*, γ^* as being typical values for the plate velocity, velocity dispersion, time, effective viscosity, structure element size and polarization, respectively. In doing so, we have:

$$\frac{\rho_1}{\rho_0}\frac{1}{U_0 t^*}W(t)=\frac{1}{\mathrm{Re}}\left\{[Q-S]+\frac{\sqrt{\nu^* t^*}}{\varepsilon^*}[DYN]\right\}; \quad (40)$$

$$W(t)=\frac{1}{\mathrm{Re}}\left\{\frac{U_0 t^*}{\varepsilon^*}[Q-S]+\frac{U_0 t^*}{\varepsilon^*}\frac{\sqrt{\nu^* t^*}}{\varepsilon^*}[DYN]\right\}; \quad (41)$$

$$\frac{c_m D^*}{U_0^2}\frac{\gamma^*}{U_0 t^*}\gamma(t)\frac{\partial D}{\partial t}+\frac{1}{\mathrm{Re}}[Q-S] + \frac{\rho_1}{\rho_0}\frac{l}{U_0 t^*}W(t)\Delta u(t)=0. \quad (42)$$

Here the terms [Q–S] denote quasi-stationary parts, and terms [DYN] describe an influence of dynamic layers.

In case where the typical deceleration time and the typical structure relaxation time are approximately equal: $t^* \sim \varepsilon^*/U_0$, Eqs. 40-42 can be written as follows:

$$\frac{\rho_1}{\rho_0}\frac{1}{\varepsilon^*}W(t)=\left\{[Q-S]+\frac{1}{\mathrm{Re}^*}[DYN]\right\}; \quad (43)$$

$$W(t)=\frac{1}{\mathrm{Re}^*}\left\{[Q-S]+\frac{1}{\mathrm{Re}^*}[DYN]\right\}; \quad (44)$$

$$\frac{c_m D^*}{U_0^2}\frac{\gamma^*}{U_0 t^*}\mathrm{Re}^*\gamma(t)\frac{\partial D}{\partial t}+\frac{1}{\mathrm{Re}^*}[Q-S] + \frac{\rho_1}{\rho_0}\frac{l}{\varepsilon^*}W(t)\Delta u(t)=0. \quad (45)$$

Eqs. 42-45 contain the following similarity criteria:

$\frac{\rho_1}{\rho_0}\frac{l}{\varepsilon^*}$ connected with a geometry of a system and density ratio;

$\frac{\gamma^*}{\varepsilon^*}$ presents rotational properties of the internal structure;

$\frac{c_m D^*}{U_0^2}$ characterizes the energy effect of mesofluctuations;

$\mathrm{Re}^*=\frac{\varepsilon^* U_0}{\nu^*}$ is the Reynolds number based on the typical structure size.

In the limiting case, $\mathrm{Re}^*\to\infty$, at high penetration velocities one has: $W(t)\to 0$, $D(t)\to$const. It means that it is the steady-state stage of penetration without the internal structure effects and the energy exchange between macro- and meso-scale levels. In other limiting case, $\mathrm{Re}^*\to 0$, the dynamic parts and the internal structure of a medium play the main role, the plate acceleration vanishes also: $W(t)\to 0$. That corresponds to the slow Stokes's flows well-known in fluid dynamics.

So, at high penetration velocities both initial and later stages can be described only with accounting the structure formation. A part of macroscopic kinetic energy of the plate determined by the velocity $U(t)$ via fluctuations being excited at mesoscopic structure scale level transforms to the velocity dispersion $D(t)$ and decreases the velocity of a solid $U(t)$-$\Delta u(t)$ by the value $\Delta u(t)$. An intensity of the energy exchange between macro- and meso-scale levels depends on medium capacity cm and an initial structure. Later, after a relaxation time meso-energy can come back to macro-level, and the slip velocity disappears. The energy exchange between macro- and meso- scale levels are supposed to be reversible. At low velocities dissipation is the leading energy exchange channel connected with the quasi-stationary parts and describing the kinetic energy transition to a heat, that is, to the molecular scale level. The intermediate scale level is not excited, and in this case all processes should be irreversible.

8. CONCLUSIONS

So, by using the developed non-local self-consistent approach an approximate solution of the boundary problem on non-stationary shear flow of a medium with accounting of the internal structure formation. The obtained solution has shown that without taking into account the dynamic structure formation it is impossible to describe high-rate deformation of a real medium in a correct way. Herewith, there is no difference between solid and liquid. In both cases the generation and evolution of rotational structures near interfaces are determined by the history of relative accelerations in merging layers.

According to the new approach, each movement in a real medium is considered to include three regimes. The first regime takes place on the initial stage of a movement, when dissipative processes have not enough time to evolve and the friction and heat transfer are determined by initial collective effects in a medium. Vibrations of the mesoscopic scale level excited by the high-rate movement of a solid lead to the mass velocity dispersion growing. An energy exchange occurs between a macroscopic movement of a solid and mesoscopic scale level at a constant thermodynamic temperature, because of the heat transfer is still absent. It should be noted that until the kinetic energy of a macroscopic movement will not transfer into the mesoscopic rotations and accumulate there, the energy exchange between macro- and meso-scale levels is reversible. In this regime the lateral friction is very small due to the large initial space correlation, and a solid, in fact, slips relative to a moveless medium. Even at steady-state high-rate movement a solid moves in this regime.

The next, transient regime is characterized by active formation of dissipative structures. In this regime dissipative structures can be both shear structures (as with the initial regime) and rotational ones. These structures are characterized by their own relaxation times depending on their scales, types and initial structures. Herewith, the medium structure parameters and macroscopic motion characteristics influence each other, in which case a feedback come into play a system. If the structure relaxation time is of order of the typical flow time, the dissipative structures are conserved even at the quasi-stationary stage and can be transported by a hydrodynamic flow. An interaction of mesoscopic structure elements and a breakage of their linear scales are followed by the energy dissipation growing with time. The energy exchange between mesoscopic and molecular scale levels becomes irreversible. Herewith, the vortical structures generate relative accelerations in a medium which have maximal values near interfaces and, in turn, generate new rotational structures. The well-known turbulent regime can be also classified as transient. In spite of the non-stationary character of a movement on the mesoscopic scale level, the mass velocity profile is of steady-state-type. If a high-rate deformation is finished before the formed structures have relaxed, the structures are frozen in a medium, as it has been observed in series of experiments on high-strain-rate loading of materials [13,14].

The last one, pure hydrodynamic regime is not realized at high-rate movement. In this regime thin shear layers near slipping rigid surfaces disappear entirely just as the rotational structures. The main effect on a friction and heat transfer is caused by the molecular viscosity and heat transfer. If a medium has an internal structure of mesoscopic scale level with a small volume concentration, in order to do not take into account the collective and spin effects, the influence of the internal structure on the hydrodynamics can be described by effective viscosity and heat conduction. The hydrodynamic regime is used to describe laminar flows of gases and fluids and also for slow flows of slightly concentrated multiphase media.

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