STRUCTURAL TRANSITIONS IN ENSEMBLES OF DEFECTS AS MECHANISMS OF FAILURE AND PLASTIC INSTABILITY UNDER IMPACT LOADING

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ABSTRACT

Using the results of direct experimental study, statistical and continuum description of mesodefect ensembles (microcracks, microshears) relaxation properties and failure kinetics in solid loaded dynamically are investigated. The correlations between nonlinear behaviour of defect ensemble, structure of stress wave, strain instability and damage localization are established.

KEYWORDS

Mesodefect ensemble, shock wave structure, strain instability, damage localization

1.INTRODUCTION

Complicate material responses to the increase of the deformation rate is observed in the nonlinear behaviour of deformation and in the changes of yield stresses of plasticity and strength. Thus a question arises whether these qausi-static characteristics can be actually used for the description of solid behaviour in a large range of the strain rate and the stress intensity. The attempts were undertaken in (Panin *et all.*, 1985; Naimark, 1995) to establish the likages of the mesodefect evolution (microcracks, microshears, grain boundaries) with relaxation properties and failure kinetics. Statistical approach allowed us to establish specific features of the defect ensemble evolution caused by the initial solid state (structural heterogeneity) and the interaction between defects. The nonlinear responses are realised during the loading as specific forms of spatial-time localized structures of defects. Scenario of defect ensemble evolution has the form of nonequilibrium kinetic transitions and which appear as a specific form of the self-similarity. This self-similarity is displayed particularly clear at plastic instability and damage localization under dynamic loading. The self-similarity in the behaviour of solid loaded dynamically is caused by the excitation of spatial-time structures in the defect ensemble. The structures are related to the eigenfunction spectrum of the corresponding nonlinear problem which is determined by nonlinearity (attractor) types of equations given by the statistical approach. The appearance of these structures is accompanied by the qualitative change of solid responses to loading. The interpretation of these phenomena as inherent properties of solid caused by nonlinear behaviour of defect ensemble allowed us to explain the evolution of the stress waves, the anomalies of the viscosity and dynamic strength at high strain rates, to propose new mechanism of adiabatic shear bands, to establish the possibility of the resonance excitation of self-keeping wave structures in defect ensembles and to connect the superdeep penetration effect with the generation of these structures.

2.STATISTICAL MODEL

Ensemble of mesoscopic defects reveals the features of the collective behaviour. The volume concentration of these defects reaches the values of about 10^{12}-10^{14} cm^{-3} and the evolution of mesoscopic defects is close to the evolution of thermodynamic systems but with very important difference: single mesoscopic defect represents the dislocation ensemble and possesses this ensemble properties. Each mesoscopic defect is the dislocation ensemble with the properties determined by the dislocation pile-up. Typical mesoscopic defects are the microcracks and the microshears. These defects can be represented by symmetrical tensors (Naimark, 1982).

$$s^n_{ik} = s^n n_i n_k, \quad s^\tau_{ik} = \frac{1}{2} s^\tau (n_i l_k + n_k l_i) \qquad (1)$$

Tensor s^n_{ik} corresponds to disk-shape microcracks with the volume $s = S_0 B$ where $S_0 = \pi R^2$ is the microcrack base and $\vec{B} = B\vec{n}$ is the total Burgers vector of the dislocation pile-up modelling mesoscopic defects. The value s^τ is the shear intensity, $\vec{n}$ is the normal vector to the slip plane, $\vec{l}$ is the slip direction. It is well known that collective properties of the dislocation pile-up are appeared in the creation of the long-range stress field, the collective mobility and the orientational instability (Indenbom and Orlov, 1984). Evolution of mesoscopic defects is caused by the statistical distribution of defect nuclei, interaction between defects and the latter with external fields. The distribution function $W(s_{ik})$ is given by the Fokker-Plank equation (Naimark, 1996)

$$\frac{\partial}{\partial t} W = -\frac{\partial}{\partial s_{ik}} \left(K_{ik}(s_{lm}) W \right) + \frac{1}{2} Q \frac{\partial}{\partial s_{ik}} \left(\frac{\partial}{\partial s_{ik}} W \right), \qquad (2)$$

where K_{ik} is the deterministic part of interaction forces, Q is the correlator which characterizes the potential relief of the initial structural heterogeneity (nonequilibrium potential). In (Botvina and Barenblatt, 1985) the statistical self-similarity of the defect distribution in solid was established for various conditions of the loading. Statistically self-similar solutions correspond to the stationary solution of the Fokker-Plank equation. The form of the solution follows from (2) for boundary conditions $W(s_{ik}) \to 0$ at $s_{ik} \to \pm\infty$

$$W = Z^{-1} \exp\left(\int_0^s 2K_{ik}(s'_{lm}) ds'_{ik} \Big/ Q \right), \qquad (3)$$

where Z is the normalizing parameter. The hypothesis of the statistical self-similarity introduces into consideration the defect distribution for which the ratio of the energy

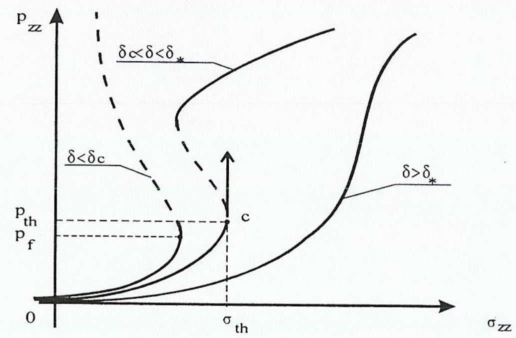

Fig. 1. Nonlinear solid responses on microcrack growth

$E = \int_0^s 2K(s'_{ik}) ds'_{ik}$ to the correlator Q is constant. The energy of the microcracks as a dislocation pile-up was estimated in (Betechtin and Vladimirov, 1979) and can be represented in a form

$$E = \left(\frac{\mu}{\pi^3 R^3} \ln \frac{R}{r_0} \right) s^2, \qquad (4)$$

where r_0 is the radius of the nuclei of the dislocation pile-up. The constraint parameter $a = \mu / (4\pi^3 R^3) \ln(R / r_0)$ depends on the volume $(\sim R^3)$ of structural elements (blocks or grains in solid). Taking into account (4) and the important role of long-range stresses produced by the defect ensemble the energy of the mesodefects was introduced

$$E = -H_{ik} s_{ik} + a s^2_{ik}. \qquad (5)$$

The effective stress field $H_{ik} = \gamma s_{ik} + \lambda n \langle s_{ik} \rangle$ determines the intensity of stress acting on the single mesodefect from the external stress field σ_{ik} and the "mean" stress field $\lambda n \langle s_{ik} \rangle$. Averaging s_{ik} with the distribution function W we obtain the self-consistency equation for microcrack density tensor $p_{ik} = n \langle s_{ik} \rangle$ (n is the microcrack concentration)

$$p_{ik} = n \int s_{ik} Z^{-1} \exp\left(E \big/ Q \right) ds d^3\vec{\nu} \qquad (6)$$

Equation (6) was solved in (Naimark, 1982) for the case of uniaxial and shear loading for various values of the dimensionless parameter $\delta = 2\alpha/(\lambda n)$ (Fig.1). The value $\lambda n \langle s_{ik} \rangle$ determines the intensity of long-range interactions in ensemble of mesodefects. There are three responses of material to the defect growth : monotonous $(\delta > \delta_*)$, metastable $(\delta_c < \delta < \delta_*)$ and unstable $(\delta < \delta_c)$; δ_* and δ_c being the bifurcation points correspond to the change of the asymptotes. The monotonous response $(\delta > \delta_*)$ is characteristic for a week interaction between defects. In metastable area the jump-like change of p_{ik} corresponds to the orientation ordering of the mesodefect ensemble. The pass over the δ_c-asymptotics leads to the infinite jump of p_{ik}. The passes over the asymptotics can be recognized as topological ansitions that lead to symmetry changes due to the new organization in the system. athematically speaking these transitions occur under the change of differential equation types d their group properties.

CONSTITUTIVE EQUATIONS

netic description of the defect growth and relation between damage and irreversible formation are based on the assumption that the free energy of material with defects depends the parameter p_{ik}, the elasticity strain tensor ε_{ik} and may be defined by statistical model . e energy of material with defects may be represented as a sum of the elastic energy and the ntribution from the defects

$$\Psi = \mu\varepsilon_{ik}'^{2} + k\varepsilon_{ll}^{2} + nF \qquad (7)$$

nere $F = \left(\lambda/2p_{ik} - Q\int \exp(-E/Q)dsd^{3}\vec{v}\right)$, ε_{ik} is elastic strain tensor; μ and K are shear and lk elastic modules . Then using the laws of conservation of mass, impulse and full energy d equation for the entropy production we may obtain the relation for the dissipative function aimark and Beljaev, 1985)

$$TP_{s} = -\frac{g_{k}}{T}\frac{\partial T}{\partial x_{k}} + \sigma_{ik}e_{ik}^{p} - \Pi_{ik}\frac{\partial p_{ik}}{\partial t} \geq 0 \ , \qquad (8)$$

re P_{s}, entropy production; T, temperature; q_{k} ,the heat flux; $e_{ik}^{p} = e_{ik} - e_{ik}^{e}$, the irreversible formation rate; e_{ik} and e_{ik}^{e} are the total and elastic deformation rates. The value $_{ik} = \partial\Psi/\partial p_{ik}$ is thermodynamic force, acting on the system if the values of p_{ik} differ from uilibrium ones. To satisfy the condition of the correctness of inequality (8) the constitutive uations should be written in a form

$$\sigma_{ik} = L_{1}e_{ik}^{p} - L_{2}\dot{p}_{ik} , \quad \Pi_{ik} = L_{2}e_{ik}^{p} - L_{3}\dot{p}_{ik} , \qquad (9)$$

nere L_{α} are material parameters. Equations (9) reveal the main mechanisms responsible for cleation and growth of microcracks: formation of critical structures (mesoscopic defect clei) with the rate proportional to the plastic deformation rate and the growth of defects fined by the free energy release. Examination of material response to deformation, made on basis of equations (9) allows us to describe a different type of deformation responses eljaev and Naimark, 1985). It is of interest to note that this has become possible without roducing axiomatic assumptions (the existence of yield stresses) and follows directly from n-linear properties of defect ensemble. What is essential in the proposed analysis is the nclusion that the threshold character of the transition to plastic flow and failure observed in asi-static experiments should be associated with the kinetic transition of the tensor structural rameter p_{ik}. Such a kinetic transition results in creation of spatial-time structures responsible plastic relaxation and damage localization.

SPATIAL-TIME STRUCTURES IN ENSEMBLE OF MESOSCOPIC DEFECTS

will be convenient to study the influence of mesoscopic defects on relaxation properties of terials to introduce the phenomenological analog of the free energy F

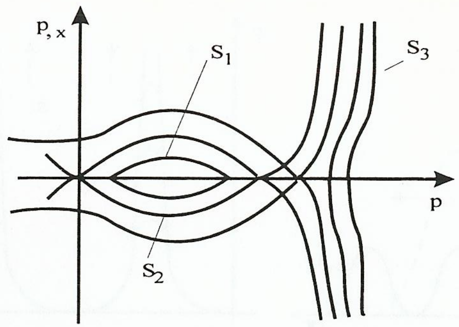

Fig. 2. Heteroclinic solution.

given by statistical approach. The simplest form can be written as the Ginsburg-Landau expansion (Naimark, 1996) of the 6-th order for $p_{ik}^{\prime}$ (the 4-th order for $p_{ik}^{\prime\prime}$)

$$F = 1/2A_{0}(1-\delta/\delta_{*})p_{ik}^{2} + 1/4B\,p_{ik}^{4} + 1/6C_{0}(1-\delta/\delta_{c})p_{ik}^{6} - D\sigma_{ik}p_{ik} + 1/2\chi(\nabla p_{ik})^{2} \quad (10)$$

The form of the coefficients upon the quadratic term and the high term provides qualitative changes of material responses on the defect growth in bifurcation points δ_{*} and δ_{c}. The gradient term in (10) describes nonlocality effects in a long wave approximation. Studying the second equation in (9) with the free energy in the form (10) we consider the bifurcation of p_{ik} for the condition of the simple shear when p_{ik} has only one component $p_{zx} = p$

$$\frac{\partial p}{\partial t} = \frac{1}{L_{3}}\left(L_{1}e^{p} - \frac{\partial F}{\partial p} + \frac{\partial}{\partial x}\left(\chi\frac{\partial p}{\partial x}\right)\right) \qquad (11)$$

The analysis of the defect evolution may be carried out due to the study of the heteroclinic solution of the equation

$$(L_{1}e^{p} + D\sigma) + A_{0}(1-\delta/\delta_{*})p + Bp^{3} - C_{0}(1-\delta/\delta_{c})p^{5} + \frac{\partial}{\partial x}\left(\chi\frac{\partial p}{\partial x}\right) = 0. \qquad (12)$$

The behaviour of such solution can be visualized on the phase portrait associated with Eqn.(12), see Figure 2. When $\delta > \delta_{*}$ solution has the form of the spatial-periodical distribution $p \rightarrow p\cdot\exp(i\phi)$ that is assimilated by media as point defects (vortices) for large scale levels. When $\delta \rightarrow \delta_{*}$ Eqn. (11) changes locally from elliptic to hyperbolic (separatrix S_{2}) and periodical solution is transformed to the solitary wave solution that corresponds to the diverge of the internal size Λ as $\Lambda \sim -\ln(\delta - \delta_{*})$, (Fig.3). The amplitude, rate of wave and the length of the wave front are determined by the parameters of the orientational transition and the nonlocal kinetics. Front of the solitary wave has the kinklike form $p(\xi) = p(x - Vt)$

$$p = 1/2p_{m}(1 - th(2\chi l_{c})^{-1}), \quad l_{c} = 4/p_{m}(2\chi L_{3})^{1/2} \qquad (13)$$

The rate of the wave propagation V is determined by the penetration depth into the metastability area $V = \chi^{1/2}/2L_{3}(p_{a} - p_{m})$, where $(p_{a} - p_{m})$ is the jump of the defect

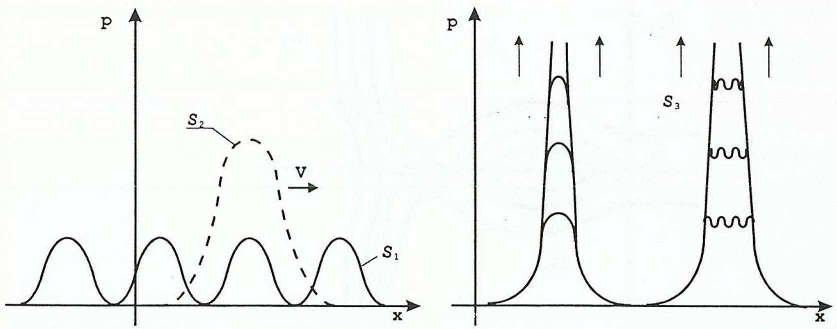

Fig. 3. Spatial-time structures in mesodefect ensembles

density parameter due to the orientational transition. The pass over the bifurcation point δ_c (separatrix S_3) gives the qualitative new type of spatial-time structures which are characterized by the explosive-like kinetics (peak regimes (Kurdyumov, 1988)) of the p-growth over some spectrum of spatial scales ς_i (Fig.3). The p-growth is subjected in this case to the singular type of the solution. The latter corresponds to the spectrum of the eigenforms of Eqn. (11) which changes locally from the hyperbolic form to parabolic one. The eigenfunction spectrum has the form

$$p(x,t) = g_i(t) f(\varsigma_i), \qquad \varsigma_i = x / \varphi_i(t) \tag{14}$$

with the singular type of the time dependence

$$g(t) = G(1 - t / t_c')^{-m}, \tag{15}$$

where $g_i(t)$ governs the growth law of p over the spectrum of the scales ς_i (the eigenvalue spectrum); φ_i defines the half-width evolution of the localization area; $G > 0$ and $m > 0$ are the parameters combined from the parameters of Eqn. (11). The passes of δ over bifurcation points lead to the generation in media with mesoscopic defects spatial structures of the various complexity controlled by different attractor types. As it was shown in (Naimark and Belyaev, 1989) the subjection of the continua to some attractors leads to the anomalies of the deformation behaviour. In solid it is realized as the fine grain state for $\delta > \delta_*$, the plastic strain localization due to the shear banding for $\delta_c < \delta < \delta_*$, and the macrocrack center nucleation due to the explosion-like damage localization for $\delta < \delta_c$. In the last case the attractor type is the strange attractor and the solid behaviour has clear stochastic features .

5. STRUCTURE OF STRESS WAVE AND FAILURE KINETICS IN SOLID UNDER IMPACT LOADING

General Equations. Structure of Stress Waves

The stress wave structure was examined in (Naimark and Belyaev, 1989a)] for the impact loading of aluminum plate collided by the quartz disk at the rate of $400 m/s$ .In the case of the

plane wave propagation in z direction the system of constitutive equations coupled with conservation laws of mass and impulse are written as

$$\sigma_{zz} = L_1 e_{zz} - L_2 \frac{\partial p_{zz}}{\partial t}, \qquad \Pi_{zz} = L_2 e_{zz} - L_3 \frac{\partial p_{zz}}{\partial t}, \tag{15}$$

$$e_{zz} = e^e_{zz} + e^p_{zz}, \qquad e^e_{zz} = \dot{\sigma}_{zz} / G + \gamma \dot{p}_{zz}, \tag{16}$$

$$\frac{\partial \rho}{\partial t} = -\frac{\partial}{\partial z}(\rho v_z), \qquad \frac{\partial v_z}{\partial t} = -\frac{\partial}{\partial z}(\rho v_z^2 - \sigma_{zz}). \tag{17}$$

The solution of system (15)-(17) has to satisfy the boundary and initial conditions:
$\sigma_{zz}(0,t) = \sigma_0(t)$, $\sigma_{zz}(h,t) = 0$; $v_z(z,0) = \sigma(z,0) = p_{zz}(z,0) = 0$; $\rho(z,0) = \rho_0$,
where h is the plate thickness, $\sigma_0(t)$-function was determined on the basis of collision problem solution. Material parameters have been determined from aluminum testing data (uniaxial tension) using direct methods of the registration of the microcrack accumulation. The parameters were taken $\rho = 2.71 \cdot 10^3 kg/m^3$, $G = 109.7 Gpa$, $\tau_m = L_1 / G = 3 \cdot 10^{-6}$ sec, $\tau_p = L_3 / G = 2.1 \cdot 10^{-6}$ sec, $\tau_x = L_2 / G = 7.5 \cdot 10^{-6}$ sec, $\tau_l = h / C_l = 1.96 \cdot 10^{-6}$ sec $\left(C_l = (G/\rho)^{1/2}\right)$. The function Π_{zz} is represented in terms of statistical integrals was approximated in the considered uni-axial loading by the nonlinear form (10). Presented in Figure 3 are the results of numerical simulation of the stress wave propagation and the time-dependencies of stress and the microcrack density parameter in the spall section. In the stress area corresponding approximately to the dynamic yield stress the orientational kinetic transition for the parameter p is realized which results in the abrupt increase in the stress relaxation tempo, a change in the plastic wave profile and the separation of the elastic precursor (bolt parts of the curves in Figure 4). A sharp transition to the highly ordered structure may lead to the abnormal deformation behaviour which has been commonly referred in dynamic problems as a failure due to the plastic shear instability. Spatial scales of the orientated area (adiabatic shear bands) are determined by the generation of the solitary wave of shear instability given by the solution (13). The rate of the transition $\dot{p}$ from the lower to upper branches reaches the maximum under the deepest penetration into the metastability area (point c in Figure 1). This is assumed to be a main reason of abnormal strain rate dependencies of viscosity on the strain rate . It is easy to see that the effective viscosity is given by the relation $\eta_{ef} = G\tau_m(1 - \tau_x / \tau_m)\dot{p} / e^p$. Taking into account the kinematic relation between e^p and $\dot{p}$ it is obvious the subjection of e^p to the orientational kinetics, i.e. $e^p \approx p$ for $p > p_{th}$. It explains the existence of the viscosity asymptotics at high strain rates. This asymptotics was observed by many authors at strain rates of about $e \sim 10^4 \div 10^6 \text{ sec}^{-1}$. From the mathematical point of view these regimes correspond to the resonance excitation of the eigenforms which are similar to the solitary wave solution. Particular clear illustration of these effects can be observed in dynamic experiments when "plugging" phenomena are realized under the strain rates $10^3 \div 10^4 s^{-1}$ produced by the collision of the hard projectile with the metal target. Under some conditions of the impact (the mass and the length of the projectile, mechanical properties of the target) the range of collision rates exists when the "plug" deformation is realised (Jonas and Zukas, 1978). Here we have developed the conception of the orientation

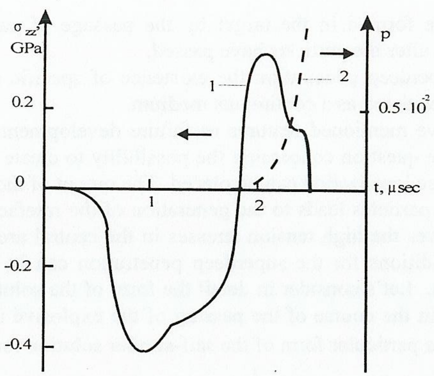

Fig. 4. Structure of stress waves and damage kinetics in spall section of aluminum target.

netic transition in the defect ensemble as possible the main reason of such anomalies. To nsider the collision problem for the long cylindrical hard projectile with the radius R pacted to the aluminum target. The modelling of this problem was reduced to the uni-axial oblem of the stress wave propagation and damage kinetics along the z-axis but for $r = R$. ne system of the equations are quite similar to the system (15)-(17) but for the components $_{z}$, p_{rz}, e_{rz}, e^{e}_{rz}, e^{p}_{rz}. The derivative $\partial\sigma_{rz}/\partial r$ was determined by the stress approximation $_{z}(r,z) \approx \sigma_{rz}(r = R,z)r^{2} / R^{2}$. The boundary condition are established for σ_{rz} and p_{rz}: $_{z}(z = 0,t) = \sigma_{0}(t)$, $p_{rz}(z = 0) = p_{rz}(z = h) = 0$. The form of $\sigma_{0}(t)$ was determined due the estimation of the kinetic energy of the projectile. The numerical simulation based on the ove mentioned scheme gives the solution in the form of two coupled waves, the strain and e defect density, having kink-like fronts (Naimark and Sokovikov, 1995). Propagation rates these waves are independent on the amplitude of the external stress starting from some tical value. The physical sense of this value is obvious that provides the reach of the critical pth in the metastability area. The front propagation rate V is determined by the kinetics of e orientation transition. The plugging occurs when the material layer with the coordinates $= R$ is involved in the condition of the shear instability. This plugging condition is realized the time of the loading is close to $\tau_{s} = h / V$. The external stress intensity during this time ist exceed the critical stress which produces the shear instability at the point σ_{th} (Fig.1). alitatively the role of the projectile is confined in the pumping of the threshold value of the ergy in the shear layer volume and then the shear instability is developed spontaneously.

ilure Kinetics in Solid under Dynamic Loading

ne of the most interesting failure phenomenon is spall fracture produced by impact loading. e spall failure is characterized by the small times ($10^{-7} - 10^{-6}$ sec) and large amplitude of nsile stresses, exceeding by several times the quasi-static limit of strength. The wave of mpressive stress induced by impact loading is reflected from the free surface of the plate get and its interaction with the wave of the unloading results in the creation of tensile stress nes. Kinetics of the microcrack accumulation is plotted in Figure 3 and reflects the pass over

the bifurcation point δ_{c} and the subjection of the defect kinetics to the peak-regime attractor. The failure kinetics, being disperse yet, exhibits some new features which are typical for the solution given by (14)-(15) The passing through the instability threshold $p = p_{f}$ involves the change of time asymptotics for p_{ik} and intensive growth of defects initiated by microcrack interaction. The explosion-like kinetics of the microcrack accumulation on spatial localised scales can be considered as the macrocrack nucleation that is accompanied by the sharp local stress decrease. Fracture due to the impact wave loading occurs in an essentially different situation relative to the quasi-static loading. Since the physical reason for the macrocrack nucleation lies in the generation of the appropriate profile of the microcrack concentration, the intensity of impact wave may produce different damage localization zones with "peak-regime" kinetics. This can be observed in the regularities of transition from a single to a multiple spall at the increased amplitude of the impact wave. In spalling the failure usually spreads over a considerable portion of the material. However, the peak regime can develop only within specific (fundamental) lengths ς_{i} with a minimum value of τ^{i}_{c}. As the load impulse increases, several structures localized on fundamental lengths are generated that corresponds to the experimentally observed transition from single to multiple spalling (Naimark and Beljaev, 1989b). In reference to Eqn. (11) the self-similarity of its solution, corresponding to the peak regime asymptotes, may account for a weak dependence of the time of failure on the impulse amplitude - the effect of "dynamic branch" (Zlatin *et al.*, 1975; Naimark and Postnykh, 1984). The regularities of the formation of localized peak- regime structures are specially vivid under shock wave loading with the duration of about 1μsec. Experiments were carried out on the rods ($10 - 12mm$ in diameter and $100 - 200mm$ long) of PMMA and ultraporcelain. The special form of a head of the specimen allowed to produce the plane rarefaction wave propagating in z-direction. A compression impulse was initiated in the rods by impact on a light-gas cannon. The parameters of the compression impulse were measured with a laser differential interferometer (Bellendir *et al.*, 1989). From the results of experimental studies of the spall fracture of rods, we plotted the logarithm of the fracture time τ_{c} versus the amplitude of the tensile stress σ_{a} (Fig. 5). At values $\tau_{c} \sim 10^{-4}$ sec, according to a fractographic analysis of spall surfaces, the development of fracture occurs due to the nucleation of one or two centers of damage localization (mirror zones) which are placed at the surface. The dependence $\log\tau_{c}(\sigma_{a})$ agrees with the time dependence of the strength of the materials which were studied during quasi-static loading. An increase in the level of the stress amplitude leads to a deviation of the $\log\tau_{c}(\sigma)$ curves (Fig.5). At the same time we observe a transition from a single-center fracture starting from the surface to a multicenter fracture (multiple mirror zones) in spall sections. Fractographic pictures of fracture are of great interest in different sections of the spalling. In the first section where the amplitude of loading impulse is maximal many mirror zones are seen on the spalling surface. Mirror zones appear to be zones of localized damage. In the section of spalling the picture is similar but the scale of mirror zones increase. In the last spall section only one or two mirror zones are formed. The numerical simulation of the damage kinetics in the term of Eqns (15)-(17) showed that

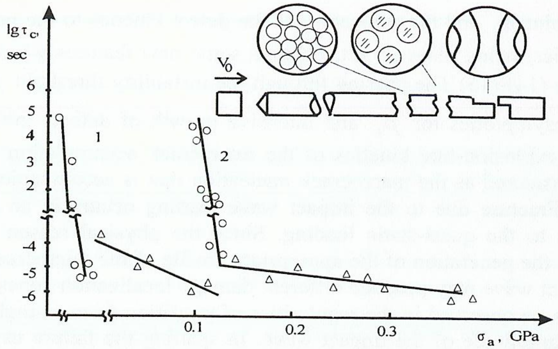

Fig. 5. Time-strength dependencies of PMMA (1) and ultraporcelain (2) (o and Δ correspond to quasi-static and dynamic branches respectively.

an intensive growth of the tensile stress in the rod leads to the formation of a multicenter fracture. The non-uniform patterns of the p-distribution in the spall section was obtained assuming the probabilistic character (normal law) of δ_c-distribution. This assumption has the natural explanation: the existence of the distribution in the sizes of the microcrack nuclei. Various damage localization scales (sizes of mirror zones) are excited in resonance regimes according to the eigenfunction spectrum for various time-dependencies of tensile stress growth in different spall sections. The transition from single-center fracture to multicenter fracture is observed in the interval of loading times $10^{-4}-10^{-6}s$. Self-similar character of damage localization as a result of the excitation of the various eigenfunction is the main factor of the weak dependence of the fracture time on the amplitude of the tensile stress ("dynamic branch", Figure 5). This result explains the "overloading" effect under dynamic fracture (Naimark and Beljaev, 1989a).

6. SUPERDEEP PENETRATION EFFECT. RESONANCE EXCITATION OF LOCALIZED DAMAGE WAVES.

Superdeep penetration is revealed in the situation when the particles of diameter $d_p \leq 100\mu m$ impacting at a velocity U between 1 and 3 km/sec penetrate into the targets (targets of *Fe, Cu, Ti, Al, Pb* and many alloys were investigated (Kozorezov *et al.*, 1981; Andilevko *et al.*, 1987)) at distances hundreds and thousands of times greater than the characteristic initial diameter of particles. This picture is not agreed with manifold experiments and theoretical results of the collision study of single bodies with the targets. Experimental investigations have revealed significant features of this effect :

(i) Superdeep penetration occurs when the flux density of powder particles exceeds $\sim 0.25 \cdot 10^3 kg/m^3$. It is not found for single particles or for low powder flux densities.

(ii) The specific energy for such particles does not exceed $5 \cdot 10^5 J/kg$ that is insufficient for the penetration to the depth greater than $50d_p$ for single particle.

(iii) The channels which are formed in the target by the passage of particles during their penetration close partly again after the particles have passed.

(iiii) It is significant for superdeep penetration the existence of specific organization of the particle flux which can be considered as a continuous medium.

Taking into account the above mentioned features of failure development as a generation of spatial-temporal structures the question concerning the possibility to create in a target the self-propagating area of the damage localization can be placed. The output of the compressive pulse on the oblique surface of the particles leads to the generation of the rarefaction waves and the interferention of the latter gives the high tension stresses in the central area of target towards the particle surface. The conditions for the superdeep penetration can be formed due to the focusing of rarefaction waves. Let's consider in detail the form of the solution of Eqn.(14) for the developed damage stage in the course of the passing of the explosive instability threshold $p=p_c$ for $\delta \leq \delta_c$. There is a particular form of the self-similar solution for Eqn.(14)

$$p_f = (St)^{-\frac{1}{l-1}} f_f(\varsigma_f), \tag{18}$$

where ς_f is a self-similar coordinate. The obtained value of ς_f and the profile of $f_f(\varsigma_f)$ allow us to define analytically the law of propagation of the damage localization area.

$$x_f = \varsigma_f K^{1/2} S^{-\frac{r}{2(l-1)}} t^{\frac{l-r+1}{2(l-1)}}, \tag{19}$$

where K and S the parameters of power expansions of Π and the nonlocality parameter χ at the point f. Equation (19) gives three of self-similarity regimes depending on the relations between the parameters of the nonlinear medium (Naimark, 1982). At $l > r+1$ the front coordinate increases in time. If the energy of the particle induces the stress level providing the nucleation of the damage localization area with parameters $l > r+1$ then the failure front will propagate in the self-keeping regime. However if the energy of the single particle could be not enough to maintain the critical stress level σ_f then the role of other particles collided at the close neighbourhood to a channel of the first particle is to provide this stress level and the conditions of the nonlinear resonance. The interaction of the particle flux with the target generates the collective wave and the relaxation of the latter is developed rather slowly.

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