Super-Deep Penetration Phenomena as Resonance Excitation of Self-Keeping Spall Failure in Impacted Materials

O. Naimark, Francis Collombet, J.-L. Lataillade

J. PHYS IV FRANCE 7 (1997)
Colloque C3, Supplément au Journal de Physique III d'août 1997

Super-Deep Penetration Phenomena as Resonance Excitation of Self-Keeping Spall Failure in Impacted Materials

O. Naimark, F. Collombet* and J.-L. Lataillade*

Institute of Continuous Media Mechanics of the Russian Academy of Sciences, 1 Acad. Korolev str., 614013 Perm, Russia
** LAMEF-École Nationale Supérieure d'Arts et Métiers, Esplanade des Arts et Métiers, 33405 Talence cedex, France*

Abstract. The anomalous responses in solid loaded dynamically are linked with the generation of the spatial-temporal structures in defect ensembles. Scenario of the evolution of typical defects (microcracks, microshears) has the form of the nonequilibrium kinetic transitions. The generation of these structures is accompanied by the qualitative changes of solid responses to loading («dynamic branch» under spalling, super deep penetration effect).

Résumé. Les matériaux soumis à des chargements dynamiques brefs et intenses ont des comportements singuliers associés à la formation spatio-temporelle d'ensembles de défauts. L'évolution de ces défauts typiques (microfissures, mïcrodéformations de cisaillement) suit le mode des transitions hors équilibres. La génèse de tels ensembles de défauts s'accompagne de changements qualitatifs de la réponse sous chargement dynamique des solides (arborescence dynamique de fissures d'écaillage, effets de super pénétration).

1. INTRODUCTION

Intensive attempts are undertaken now to explain the enigmatic phenomenon - super deep penetration effect. However, traditional approaches of solid mechanics don't allow the explanation of this effect and many researchers pointed out the qualitative new material responses on the intensive loading that are not described by the well-known mechanical models and it requires to develop the new outlook on the material ability to the stress relaxation and failure kinetics based on the consideration of essentially nonlinear properties of materials caused by defects.This direction has been developed theoretically and experimentally in [1,2]. Non-traditional responses of solid with defects were predicted firstly in [3,4] on the basis of the statistical description of the defect evolution that allowed the establishment of the various forms of localized instabilities in defect ensembles which lead to self similar laws of failure and plasticity development. These results allowed us to develop the continuum description of nonlinear responses of solid with defects and to consider the appearance of the resonance excitation of the dissipative structures of defects in impacted solid. The direct experimental investigation of failure structures was carried out in [5] due to study of self-similar response of impacted solid ("dynamic branch" under spalling). Theoretical analysis showed that the self-similar responses of impacted solid are the consequence of the resonance excitation of the propagating dissipative structures of defects with a "peak regime" kinetics. Qualitative similar conditions are realized due to the collision of particle clusters with a targets. It was established that the creation of the longitudinal channels and the anomalous particle penetration are realized due to the rarefaction wave propagation produced by the particle collision and the generation in these waves self-keeping failure structures corresponding to the eigenfunction spectrum with explosion-like damage kinetics.

2.CONSTITUTIVE EQUATIONS

Ensemble of typical defecs (microcracks, microshears) reveals the features of the collective behaviour. The volume concentration of these defects reaches the values of about $10^{10}-10^{14}\,cm^{-3}$ and the evolution of defects is close to the evolution of thermodynamic systems but with very important difference: single mesoscopic defect represents the dislocation ensemble and possesses these ensemble properties. Typical mesoscopic defects are the microcracks and the microshears. These defects can be represented by symmetrical tensors [6] :

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

Tensors s^n_{ik} and s^τ_{ik} correspond to microcracks and microshears. The values s^n and s^τ are the microcrack volume and the shear intensity, $\vec{n}$ is the normal vector to the defect base, $\vec{l}$ is the slip direction. Statistical approach that was developed in [1] allowed the determination of characteristic solid responses on the defect growth. As result of the statistical averaging with the distribution function given by the solution of the Fokker-Plank equation the macroscopic tensor of the microcrack (microshear) density $p_{ik} = n\langle s_{ik}\rangle$ was determined (n is the microcrack concentration). It is evidence that p_{ik} gives the deformation caused by the defects. The important consequence of the statistical approach is the form of the free energy. The energy of materials with defects may be represented as a sum of the elastic energy and the contribution from the defects :

$$\Psi = \mu\varepsilon'^2_{ik} + k\varepsilon^2_{ll} + F, \qquad (2)$$

where F is the part of the free energy caused by defects, ε_{ik} is the elastic strain tensor; μ and k are shear and bulk elastic modules . The simplest form of free energy which reflects the typical nonlinearities caused by defects can be written as the Ginsburg-Landau expansion [6] of the 6-th order for the microshear density tensor (the 4-th order for microcrack density tensor) :

$$F = 1/2A_0(1-\delta\ \delta_*)p^2_{ik} + 1/4Bp^4_{ik} - 1/6C_0(1-\delta/\delta_c)p^6_{ik} - D\sigma_{ik}p_{ik} + 1/2\chi(\nabla p_{ik})^2 \cdot \qquad (3)$$

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 (3) describes nonlocality effects in a long wave approximation. Using the laws of the conservation of mass, impulse and total energy and equation for the entropy production we may obtain the relation for the dissipative function [1] :

$$TP_s = -\frac{q_k}{T}\frac{\partial T}{\partial x_k} + \sigma_{ik}e^p_{ik} - \Pi_{ik}\frac{\partial p_{ik}}{\partial t} \geq 0, \qquad (4)$$

here, P_s, entropy production; T, temperature; q_k, the heat flux; $e^p_{ik} = e_{ik} - e^e_{ik}$, the irreversible deformation rate; e_{ik} and e^e_{ik} are the total and elastic deformation rates. The value $\Pi_{ik} = \partial\Psi / \partial p_{ik}$ is thermodynamic force, acting on the system if the values of p_{ik} differ from equilibrium ones. To satisfy the condition of the correctness of the inequality (4) the constitutive equations should be written in a form :

$$\sigma_{ik} = L_1 e^p_{ik} - L_2 \dot{p}_{ik}; \qquad \Pi_{ik} = L_2 e^p_{ik} - L_3 \dot{p}_{ik}, \qquad (5)$$

where L_α are material parameters. Equations (5) reveal the main mechanisms responsible for nucleation and growth of microcracks: the formation of critical structures (defect nuclei) with the rate proportional to the plastic deformation rate and the growth of defects defined by the free energy release.

3. SPATIAL-TEMPORAL STRUCTURES IN ENSEMBLE OF DEFECTS

The influence of the defects on nonlinear properties of materials can be considered on the basis of the heteroclinic solution.

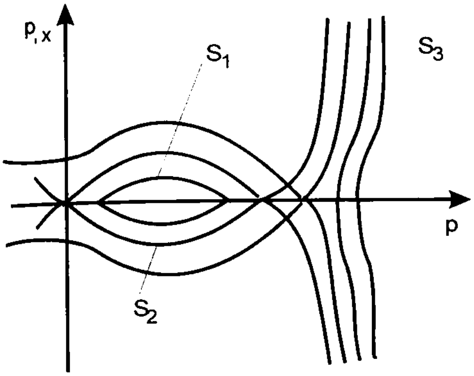

Figure 1: Heteroclinic solution.

Studying the second equation in (5) with the free energy in the form (3) we consider the bifurcation of p_{ik} for the condition of the simple shear when p_{ik} has only one component $p_{xz} = p$ (for microcrack density tensor the situation is the same) :

$$\frac{\partial p}{\partial t} = \frac{1}{L_3}\left(L_1 e^{p} - \frac{\partial F}{\partial p} + \frac{\partial}{\partial x}\left(\chi \frac{\partial p}{\partial x}\right)\right) \quad (6)$$

The heteroclinic forms are given by the solution of the equation :

$$\left(L_1 e^{p} + D\sigma\right) + A_0\left(1 - \delta/\delta_*\right)p + Bp^3 - C_0\left(1 - \delta/\delta_c\right)p^5 + \frac{\partial}{\partial x}\left(\chi \frac{\partial p}{\partial x}\right) = 0. \quad (7)$$

The solution can be visualized on the phase portrait associated with Eqn.(7), see Figure 1. When $\delta > \delta_*$ the solution has the form of the spatial-periodical distribution $p \to p \cdot \exp(i\phi)$ that is assimilated by media as point defects (vortices) for large scale levels. When $\delta \to \delta_*$ Eqn. (7) 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.2). 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 kink-like form :

$$p(\xi) = p(x - Vt), \quad p(\xi) = 1/2p_a\left(1 - \mathrm{th}\left(2\xi l_c^{-1}\right)\right), \; l_c = 4/p_a(2\chi V)^{1/2} \quad (8)$$

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 density parameter due to the orientation transition.

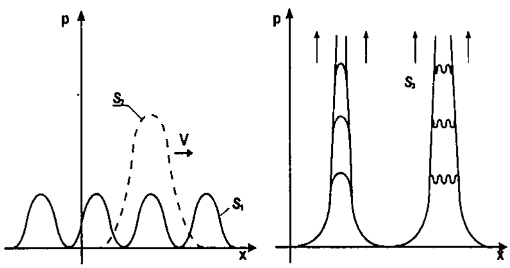

Figure 2: Spatial-time structures in the defect ensembles.

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 [1]) of the p-growth over some spectrum of spatial scales ζ_i (Fig.2). 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. (6) which changes locally from the hyperbolic form to parabolic one.The eigenfunction spectrum has the form :

$$p(x,t) = g_i(t) f(\varsigma_i), \quad \varsigma_i = x / \varphi_i(t) \qquad (9)$$

with the singular type of the time dependence :

$$g(t) = G(1 - t / t_c^i)^{-m}, \qquad (10)$$

where $g_i(t)$ governs the growth law of p over the spectrum of the scales ζ_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. (6). The passes of δ_c 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 [7] 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 stochastic features.

4. SELF-SIMILAR SOLID RESPONSE UNDER SPALLING

One of the most interesting failure phenomenon is spall fracture produced by impact loading. The spall failure is characterized by the small times ($10^{-7} - 10^{-6}$ sec) and large amplitude of tensile stresses, exceeding by several times the quasi-static limit of strength. The wave of compressive stress induced by impact loading is reflected from the free surface of the plate target and its interaction with the wave of the unloading results in the creation of tensile stress zones. Kinetics of the microcrack accumulation is plotted in Figure 3 and reflects the pass over the bifurcation point p_c and the subjection of the defect kinetics to the peak-regime attractor. The failure kinetics, being disperse yet, exhibits some new features. The passing through the instability threshold $p = p_c$ involves the change of time asymptotics for p_{ik} and intensive growth of defects initiated by microcrack interaction. In spalling the failure usually spreads over a considerable portion of the material. However, the peak regime can develop only within specific (fundamental) lengths ζ_i with a minimum value of. t_c^i. 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 [3]. The subjection of the damage to the peak-regime kinetics explains the so-called "dynamic branch" of the failure time dependence on the stress amplitude [5].

The regularities of the formation of localized peak-regime structures are specially vivid under shock wave loading with the duration of about $1\mu sec$. Experiments were carried out on the rods (10-12 mm in diameter and 100-200 mm long) of PMMA and ultraporcelain. 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 [5]. 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_c (Fig.3). 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.3). 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 showed that an intensive growth of the tensile stress in the rod leads to the formation of a multicenter fracture. 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 various eigenfunctions is the main factor of the weak dependence of the failure time on the amplitude of the tensile stress (Fig.3). This result explains the "overloading" effect under dynamic fracture [3].

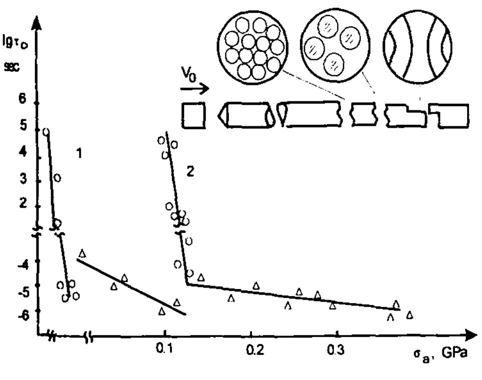

Figure 3: Time-strength dependencies of PMMA (1) and ultraporcelain (2) (o and Δ correspond to quasi-static and dynamic branches respectively.

5. 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 between 1 and 3 km/sec penetrate into the targets (targets of *Fe, Cu, Ti, Al, Pb* and many alloys were investigated [7,8]) 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.

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 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 super deep penetration can be formed due to the focusing of rarefaction waves. Let's consider in detail the form of the solution of Eqn.(6) 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.(9) :

$$p_f = (St)^{-\frac{1}{l-1}} f_f(\varsigma_f), \qquad (10)$$

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 :

$$x_f = \varsigma_f K^{1/2} S^{-\frac{r}{2(l-1)}} t^{\frac{l-r+1}{2(l-1)}}, \qquad (11)$$

where K and S the parameters of power expansions of Π and the nonlocality parameter χ at the point p_f. Equation (11) gives three of self-similarity regimes depending on the relations between the parameters of the nonlinear medium [1]. 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.

REFERENCES

[1]: Naimark O., 1982,*"On thermodynamics of deformation and fracture of solids with microcracks"*, Preprint of the Institute of Continuous Media Mechanics, USSR Academy of Sciences, Sverdlovsk (in Russian).

[2]: Naimark O., 1995, "*Kinetic transitions in ensembles of defects and mechanisms of plasticity andf failure*", Preprint of the Institute of Continuous Media Mechanics of the Russian Academy of Sciences, Perm.

[3]: Bejaev V., Naimark O., 1990, Kinetics of multicenter fracture under shock wave loading, *Sov. Phys. Dokl.*,Vol. 312, n° 2, pp.289-293.

[4]: Beljaev V., Naimark O., 1985, Kinetic transitions in media with microcracks and metal fracture in stress waves. *J. Appl. Mech. Tech. Phys.*, n° 1, pp.163-171.

[5]: Bellendir E., Beljaev V. and Naimark O., 1989, Kinetics of multicenter fracture under spalling conditions, *Sov. Tech. Phys. Lett.*, Vol. 15, n° 13, pp.90-934.

[6]: Naimark O., 1997,. "Structural transitions in ensembles of defects as mechanisms of failure and plastic instability under impact loading", Proc. *IX Int. Conf. Fracture. Sydney,* Vol.6, pp.2795-2806.

[7]: Andilevko S., Roman O., Romanov G. and Usherenko S., 1987, "Superdeep penetration of powder particles with solid materials", *Soviet Powder Metallurgy and Metal Ceramics*, n° 11, pp. 6-11 (in Russian).

[8]: Kozoresov K., Maksimenko V. and Usherenko S., 1981, "Study of interaction of microparticles with solid materials", In: *Selected Problems of Modern Mechanics,* Moscow University, Moscow, Vol. 1, pp.12-36 (in Russian).