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Collective Modes in the Microshear Ensemble as a Mechanism of the Failure Wave

O. Naimark,[1] O. Plekhov,[1] W. Proud,[2] and S. Uvarov[1,a]

[1] Institute of Continuous Media Mechanics, Russian Academy of Sciences, Perm, Russia

[2] Cambridge University, Department of Physics, Cavendish Laboratory, Cambridge, UK

[a] usv@icmm.ru

Results of theoretical and experimental study of failure wave phenomena are presented. A description of the failure wave phenomenon was proposed in terms of a self-similar solution for the microshear density. The mechanisms of failure wave generation and propagation were classified as a delayed failure with the delay time corresponding to the time of excitation of self-similar blow-up collective modes in a microshear ensemble. Experimental study of the mechanism of the failure wave generation and propagation was carried out using a fused quartz rod and included the Taylor test with high-speed framing. The results obtained confirmed the "delayed" mechanism of the failure wave generation and propagation.

Keywords: mesodefect evolution, failure waves.

Introduction. The phenomenon of a failure wave in brittle materials has been the subject of intensive study during the last two decades [1–3]. The term "failure wave" was introduced by Galin and Cherepanov [4] as the limit case of damage evolution, where the number of microshears is large enough for the determination of the front with a characteristic group velocity. This front separates the structured material from the failed area. Rasorenov et al. [1] were the first to observe the phenomenon of delayed failure behind an elastic wave in glass. Such a wave was introduced by Brar and Bless in [5], where the concept of a fracture wave was discussed to explain the nature of the elastic limit. A failure wave appeared in shocked brittle materials (glasses, ceramics) as a particular failure mode in which they lose strength behind the propagating front. Generally, the interest to the failure wave phenomenon is initiated by the still open problem of physical interpretation of traditionally used material characteristics such as the Hugoniot elastic limits, dynamic strength, and relaxation mechanism of elastic precursor.

Qualitative changes in silicate glasses behind the failure wave, e.g., an increase in the refractive index, allowed Gibbons and Ahrens (1971) to qualify this effect as the structural phase transformation. These results stimulated Clifton [6] to propose a phenomenological model in which the failure front was assumed to be a propagating phase boundary. According to this model, the mechanism of failure wave nucleation and propagation results from the local densification followed by shear failure around the inhomogeneities triggered by the shock.

Using high-speed photography, Paliwal et al. [7] obtained real-time data on the damage kinetics during dynamic compressive failure of a transparent AlON. The results suggest that final failure of the AlON under dynamic loading was due to the formation of a damage zone with unstable propagation of the critical crack.

Statistical Model. The description of the failure wave phenomenon was proposed by Naimark et al. [8, 9] after analyzing the damage localization dynamics in terms of a self-similar solution for the microshear density. This solution describes qualitative changes in the microshear density kinetics that allows defining failure waves as a specific ("slow dynamics") collective mode in the microshear ensemble that could be excited due to the pass of a shock wave. Structural parameters associated with typical mesodefects were introduced as a macroscopic tensor of the defect density , which coincides with the deformation induced by defects. Taking into account the large number of mesoscopic defects and the influence of thermal and structural fluctuations involved in the damage accumulation process, the formulation of a statistical problem concerning the defect distribution function was proposed by Naimark [9] in terms of the solution to the Fokker-Plank equation in the phase space of characteristic mesodefect variables.

The statistical description allowed us to propose a model of a solid with defects based on the appropriate free energy form. A simple phenomenological form of the part of free energy caused by defects (for the uniaxial case) is given by a sixth order expansion, which is similar to the Ginzburg–Landau expansion in the phase transition theory [9]:

$$F = \frac{1}{2}A(1-\delta/\delta_*)p^2 - \frac{1}{4}Bp^4 - \frac{1}{6}C(1-\delta/\delta_c)p^6 - D\sigma p + \chi(\nabla_l p)^2. \qquad (1)$$

Here the gradient term describes non-local interaction in the defect ensemble; A, B, C, and D are positive phenomenological material parameters, and χ is the nonlocality coefficient. The damage kinetics is determined by the evolution inequality

$$\partial F/\partial t = (\partial F/\partial p)\dot{p} + (\partial F/\partial \delta)\dot{\delta} \le 0, \qquad (2)$$

that leads to kinetic equations for the defect density p and scaling parameter δ:

$$\dot{p} = -\Gamma_p (\partial F/\partial p - \partial/\partial x_l\, (\chi\, \partial p/\partial x_l\,)), \qquad (3)$$

$$\dot{\delta} = -\Gamma_\delta\ \partial F/\partial \delta, \qquad (4)$$

where Γ_p and Γ_δ are kinetic coefficients. Analysis of Eqs. (3) and (4) shows that the scaling parameter δ determines the reaction of a solid to the defect growth. If $\delta < \delta_c$, the evolution of the defect ensemble is governed by spatial-temporal structures (S_3) of a qualitatively new type characterized by an explosive ("blow-up") accumulation of defects as $t \to \tau_c$ in the spectrum of spatial scales. The "blow-up" self-similar solution is the precursor of the crack nucleation due to a specific kinetics of damage localization,

$$p = g(t)f(\xi), \quad \xi = x/L_c, \quad g(t) = G(1-t/\tau_c)^{-m}, \qquad (5)$$

where τ_c is the so-called "peak time" ($p \to \infty$ at $t \to \tau_c$), L_c is the scale of localization, and $G > 0$ and $m > 0$ are the parameters of non-linearity, which characterise the free energy release rate for $\delta < \delta_c$. The function determines the defect density distribution in the damage localization area. Equation (3) describes the characteristic stages of damage evolution. As the stress at the shock wave front approaches the critical value σ_c, the properties of the kinetic equation (3) change qualitatively (for $p \to p_c$) and the damage kinetics is subject to the self-similar solution [Eq. (5)]. The method for the solution of this problem was developed by Kurdjumov [10]. It allowed the estimation of $\bar{\xi}_f$ and the definition of the failure front propagation kinetics:

$$x_f = \bar{\xi}_f \chi_0^{1/2} S^{-\omega/[2(\beta-1)]} t^{(\beta-\omega+1)/[2(\beta-1)]}. \qquad (6)$$

Equation (6) determines self-similar regimes of the failure wave propagation, which depends on the values of the parameters β and ω. For instance, for the values of the parameters $\beta \approx \omega + 1$, a failure wave will be generated as the subsequent excitation of a "blow-up" damage localization area arising after the shock wave pass with the delay time t_c.

Numerical simulation of the damage kinetics [11] based on Eq. (6) for the conditions of the plate impact test confirmed the mechanism of the failure wave generation predicted by the aforementioned self-similar solution (Fig. 1).

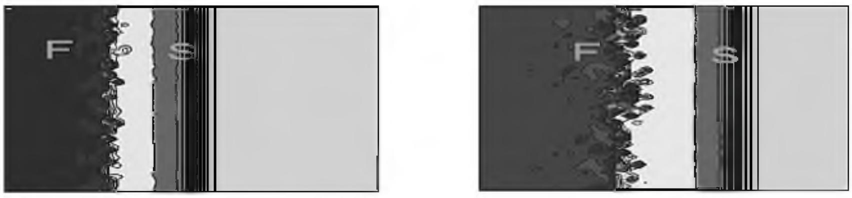

Fig. 1. Simulation of the shock (*S*) and failure (*F*) wave propagation for the condition of the plate impact test. The photos correspond to different times of the shock and failure wave propagation.

Experiment. An experimental study of the failure wave generation and propagation was realized for the symmetric Taylor test performed on 25 mm-diameter fused-quartz rods [11]. Figure 2 shows processing of photos obtained by a high-speed photography for an experiment with a flyer rod traveling at 534 m/s at impact. The flyer rod was traveling from the left to the right. In the first frame (0.3 μs after impact), two vertical dark lines are observed. The line on the left is the impact surface. The line to the right is a shock wave that can be clearly seen propagating at a higher velocity in front of other waves in the subsequent frames.

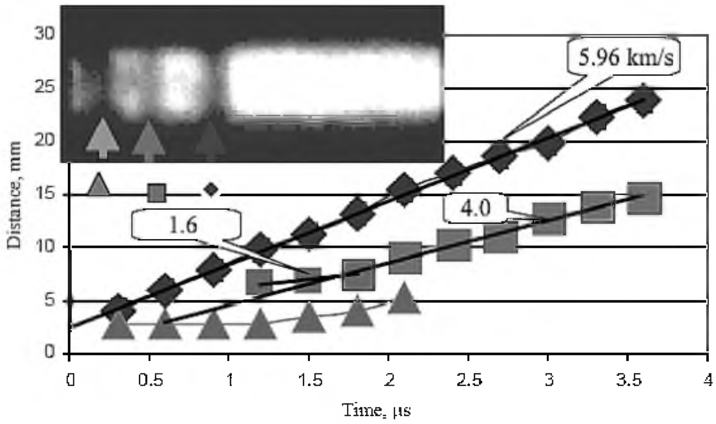

Fig. 2. Processing of high-speed photos of the shock and failure wave propagation. Three dark zones correspond to the images of the impact surface (▲), failure wave (■), and shock wave (◆).

Based on the measurements from the photographs, the first front was calculated to slow down from the velocity approximately equal to the longitudinal wave speed in fused quartz (5.96 km/s) during the initial 2.1 μs after impact to 5.2 ± 0.3 mm/μs after 3.9 μs. Another front is observed in the frames labeled 1.5 and 1.8 μs after impact. By the 2.1 μs after impact, it became the failure front (marked by a square). The 1D strain state will exist until the release waves from the outer edges converge along the center of the specimen. Therefore, the development of failure is under the same conditions as those experienced during the plate impact, including the transition to the 1D stress state.

The second front appears at the 1.2 μs (0.6 μs after the first (elastic) front passes this point). It is interesting to note that the second front appearing at the 1.2 μs does not advance significantly until the material behind it becomes fully comminuted (opaque). During this time the front velocity is $V_{fw} \approx 1.57$ km/s, which is close to that traditionally measured in the plate impact test. However, the following scenario reveals an increase in the failure front velocity up to $V_{fw} \approx 4$ km/s. The fact that the failure wave front velocity approaches the shock front velocity supports the theoretical result concerning the failure wave nature as "delayed failure" with the limit of the "delay time" corresponding to the "peak time" in the self-similar solution (5). The loss of transparency is caused by the defect nucleation and occurs during the "blow-up" time after the induction time τ_I (the time of the formation of the self-similar profile of defect distribution). Failure occurs after the delay τ_d, which is the sum of the induction time τ_I, and the "peak time" τ_c (the time of the "blow-up" damage kinetics). The steady-state regime of the failure wave front propagation can be associated with the successive activation of the "blow-up" dissipative structures under the condition where $\tau_d \approx \tau_c$.

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