

MESODEFECT INDUCED MECHANISMS OF PLASTICITY AND FAILURE IN SHOCKED SOLIDS

Yu. Bayandin, O. Naimark

Institute of Continuous Media Mechanics, UB of RAS, Perm, Russia

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1. Abstract

Based on statistical thermodynamics the model for solids with mesodeflects (microcracks and microshears) was developed. To confirm the self-similar nature of the plastic wave front theoretical study of relaxation mechanisms was carried out using the constitutive model of solid with mesodeflects. Experimental results and numerical calculations for plane shock wave propagation and spall failure are discussed.

2. Statistical model

The developed statistical model of solid with mesoscopic defects allowed the formulation of phenomenological model in terms of two independent variables - the defect density tensor and structural scaling parameter and the simulation of shock wave propagation in the linkage with structural relaxation phenomena [1,2]. It was established the link of the Hugoniot elastic limit with kinetics of structural transition (mathematically related to the defect density tensor) in the structural metastability area, that has generally thermally-activated character. The development of plastic front is described as the consequence of self-consistent structural (orientation) transition in microshear ensemble that is realized due to the kinetics of structural scaling parameter.

Based on the statistical theory [2] the mathematical model was proposed for plane shock wave propagation in metal. The mechanisms of plasticity, induced by correlated behavior of microshear ensembles, were studied [1,3] in the of internal structural variables – the defect density tensor and the structural scaling parameter. The defect density tensor (microshear induced strain) was introduced as the mean value $p_{ik} = n \langle s_{ik} \rangle$ of “microscopic” shear tensor

$$(1) \quad s_{ik} = 1/2s(v_i l_k + l_i v_k),$$

where \vec{v} is unit vector normal to slip plane of a microscopic shear; \vec{l} is a unit vector in the direction of shear; s is the shear intensity, n is the microshear density. The statistical theory allowed us to establish the second internal variable for continuum with mesodeflects – the structural scaling parameter δ associated with two characteristic structural scales: the mesodeflect nuclei and the distance between defects. The plastic deformation is described in terms of mentioned variables as the structural-scaling transition and corresponds to the scenario of continuous orientation transition in the microshear ensemble along the structural scales.

According to statistical theory these transitions are realized as the multiply metastability of non-equilibrium free energy that for the uni-axial case ($\mathcal{E}_{xx} = \mathcal{E}, p_{xx} = p$) is given by the following nonlinear form

$$(2) \quad \Psi = F/F_m = \frac{p^2}{2\delta} - \left(\frac{p^2}{2} + 0.188p + 0.507 \text{Log}(0.385 + 0.131p + p^2) \right) + \frac{\Sigma p}{\delta},$$

where F_m is energy scale, Σ - dimensionless stress.

3. Results and discussions

Results of numerical calculations for single shock in the Armco iron are presented in papers [1,3]. It was shown that the self-similarity of the plastic shock-wave fronts in solids is the consequence of existence of two independent mechanisms defining structural relaxation. These mechanisms are related to the structural-scaling transition in terms of two independent variables (defect density tensor and structural-scaling parameter). The kinetics of these two characteristic variables (order parameters) at the steady-state plastic wave fronts is realized in the self-criticality regime with generation of auto-solitary strain modes that provides the self-similar scenario of relaxation on the large range of structural scales.

In present investigations a setup for plate impact experiment has been developed at Institute of Continuous Media Mechanics of Ural Branch of RAS to study dynamic fracture at strain rates up to 10^6 s^{-1} . Experiments were carried out at a different impactor velocity in order to investigate dependency on loading conditions.

The numerical simulation of plane shock wave propagation was carried out to establish spall conditions and to propose the mechanism of damage-failure transitions described as a specific form of self-organized criticality in the ensemble of mesoscopic defects – structural-scaling transition. Characteristic features of this transition are the generation of collective modes in mesodefekt ensemble that are responsible for damage localization and transition to failure. Collective modes have the nature of self-similar solution and describe the blow-up damage localization kinetics with characteristic time (peak-up time) on the set of spatial scales. Mechanism of spall failure can be linked with resonance excitation of blow-up collective modes and has the nature of delayed failure with the delay time corresponding to the peak-time of the self-similar solution.

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5. References

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