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Kinetics theory of shock-induced structural heterogenization

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Abstract

In considering the shock wave propagation in solid, instead of traditional constitutive equation, the lockingof balance equations is conducted by using the mesoparticle velocity distribution function. In this approach, the dynamically deformed material is considered to be the stochastic medium and the particle velocity and velocity dispersion are determined as the first and second statistical moments of distribution function. Meso-macro- energy exchange is found to be realized through change of the particle velocity dispersion – the second moment of distribution function. The criterion for transition from evolutional regime of meso-macro energy exchange to heterogenization is found to be determined by the ratio of rate of change the velocity dispersion and particle velocity acceleration.

Keywords: shock wave; particle velocity; dispersion; velocity variance; time of relaxation; macro-meso energy exchange

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1. Introduction

Experimental and theoretical investigation of shock-induced dynamic heterogenization of structure of solids remains to be actual problem both in physics of high pressures and mechanics of high-velocity deformation and fracture of materials. Mechanics of multiscale deformation faces two main problems: (i) absence of constitutive equations for each of sub-levels of dynamic straining; (ii) unclear mechanism of interaction between scale levels.There are several approaches to description of multiscale processes of structure formation. To date, one of the most widely spread models are based on molecular dynamics techniques (see, for example, Holian and Lamdahl, 1998, Krivtzov, 1999). In these models, for the mutual interaction of particles the Lennard-Johns potential, Morse potential and other kinds of potentials are used.

Oneofalternativeapproachesto the problem of structure formation is recently developed by Khantuleva (2000, 2002).The technique is grounded on the fundamental results of non-equilibrium statistical mechanics, developed by Zubarev (1978). Inthistheory, thebalanceequationsarelockedwithnon-localequationwhichcontainsthe integral characteristics of deformed medium, such as scale of non-locality and degree of polarization of medium. The latter is caused by the non-local character of interaction of structural elements. Tofindingtheabovecharacteristics, avelocitygradienttechniquefordynamicvariablesdevelopedbyFradkov (1977) isused.

In the present paper, an attempt is undertaken to solve the problem of structure formation on the basis of the fact that high-velocity deformation is a certainly stochastic process. This allows to consider the motion of shock wave in solid as a superposition of two modes: (i) a mean motion of shock front which is of approximately plane shape, and (ii) a small rapidly fluctuating motion of medium about this mean motion due to the action of random micro-fields of internal stresses.The purpose of the present paper is to find the criterion for transition from uniform dynamic deformation to heterogeneous regime.

2. Meso-macroenergyexchangeandpropagationofshockwaveinamediumwiththeparticlevelocitydispersion

Analysisof shock-wave experimentsshowsthatthereisasaminimumtworegimesofenergyexchangebetweenmacro- andmeso- scalesofdynamicdeformation – evolutionaland “catastrophic” In the second case, the particlevelocitydispersiongrowsveryfastwhereasthemeanparticlevelocitydrops.

Thecheckingofthatfacthasbeenmadeinshocktestsofdifferentmaterials. For copper it has been made with shock loaded copper by Meshcheryakov et. al (2008).

To find the criterion for changing the energy exchange regime, consider a propagation of plane shock wave. In one-dimensional case, the motion of medium is described by two balance equations - impulse conservation equation and equation of continuity of medium

$$\rho \frac{\partial u}{\partial t} = \frac{\partial \sigma}{\partial x}, \quad \frac{\partial u}{\partial x} = \frac{\partial \varepsilon}{\partial t} \qquad (1)$$

The second equation can be expressed through the elastic and plastic components of strain rate:

$$\frac{\partial u}{\partial x} = \frac{\partial \varepsilon^e}{\partial t} + \frac{\partial u^{pl}}{\partial x}. \qquad (2)$$

Then the balance equation can be reduced to second order differential equation:

$$\frac{\partial^2 u}{\partial x^2} - \frac{1}{C_l^2}\frac{\partial^2 u}{\partial t^2} = \frac{\partial^2 u^{pl}}{\partial x^2} - \frac{1}{\rho C_l^2}\frac{\partial^2 \sigma}{\partial x \partial t}. \qquad (3)$$

where $C_l = \left(\frac{\lambda + 2\mu}{\rho}\right)^{\frac{1}{2}}$ is the longitudinal sound velocity. The elastic components of deformation and stress are linked with Hook’s law

$$\sigma_1^e = (\lambda + 2\mu)\varepsilon_1^e.$$

Consider in details the right hand side of Eq.(3). In the case of unsteady plastic wave, the plastic particle velocity,u^{pl}, can be subdivided by equilibrium and non-equilibrium components:

$$u^{pl} = u_p^{pl} + u_н^{pl}, \qquad (4)$$