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Fracture, electric breakdown and phase transformations under impact loading

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Abstract

A unified interpretation of dynamic effects, which are common for a series of seemingly quite different physical processes such as pulsed fracture of solids, electric breakdown, and phase transitions under the action of fast energy fluxes is given. This general treatment is possible using the structural-temporal approach based on the notion of process incubation time.

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Keywords: Dynamic fracture; electric breakdown; phase transformation; shock freezing; impact loading; rate effects; incubatiobn time criterion.

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1. Introduction

One of the basic problems in testing mechanical and electric strength properties of materials is associated with the dependence of the limiting strength characteristics on the duration, amplitude, and growth rate of an external action, as well as on a number of other factors. This and some other specific features of continuum behavior under pulse actions are common for a series of seemingly quite different physical processes such as pulsed fracture of solids, electric breakdown, and phase transitions (melting, crystallizing) under the action of fast energy fluxes. The main reason of that is the united spatio-temporal nature of fracture and structural transformations. In the present paper examples illustrating typical dynamic effects in the abovementioned processes are

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considered. A unified interpretation of dynamic fracture of solids and fluids, electric breakdown, and phase transitions using the structural-temporal approach based on the notion of process incubation time is given.

2. Incubation time approach to dynamic fracture

The main difficulties in modeling the dynamic effects of mechanical strength, yielding and phase transitions is the absence of an adequate limiting condition that determines the possibility of rupture, yield or phase transform. The problem can be solved by using both the structural fracture macromechanics and the concept of the incubation time of the corresponding process, representing nature of kinetic processes underlying formation of macroscopic breaks, yield flow or phase transformation. The above effects become essential for impacts with periods comparable to the scale determined by the fracture incubation time that is associated with preparatory relaxation processes accompanying development of micro defects in the material structure.

The criterion of fracture based of a concept of incubation time (Petrov (1991), Petrov and Morozov (1994), Morozov and Petrov (2000)) makes it possible to predict unstable behavior of dynamic-strength characteristics. The criterion can be generalized to the following limiting condition:

$$\frac{1}{\tau}\cdot\int_{t-\tau}^{t}\left(\frac{F(t')}{F_c}\right)^{\alpha}dt' \le 1\,. \tag{1}$$

Here, $F(t)$ is the intensity of a local force field causing the fracture (or structural transformation) of the medium, F_c is the static limit of the local force field, and τ is the incubation time associated with the dynamics of a relaxation process preparing the break. It actually characterizes the strain (stress) rate sensitivity of a material. The fracture time t_* is defined as the time at which condition Eq. (1) becomes equality. The parameter α characterizes the sensitivity of a material to the intensity (amplitude) of the force field causing fracture (or structural transformation).

As has been demonstrated previously (Petrov (1991), Petrov et al (2003), Petrov and Sitnikova (2005)) the set of special cases of the dynamic fracture criterion (1) successfully predicts fracture initiation in brittle solids. For high loading rates when the times to fracture are comparable with τ, a variety of effects observed in dynamic fracture experiments has been explained qualitatively and quantitatively using incubation time approach (some were summarized in the monograph by Morozov and Petrov (2000)).

3. Electric breakdown

Experiments on the breakage of continuous media and the breakdown of vacuum and dielectric gaps under the pulse action of mechanical stresses or of electric voltage have revealed a number of effects that show the principal difference between a fast dynamic fracture (breakdown) and a similar process during slow quasistatic actions. In the case of the electric strength, this function is expressed by the experimentally measured voltage–time characteristic dependent on a number of parameters of both the applied pulse and the breakdown gap including the material of electrodes, their geometry, the microrelief of surfaces, and other characteristics substantially affecting autoemission currents, the leading role of which in the mechanism of initiation of the discharge is reasonably full investigated in numerous works. Under slow action, it is a phenomenological criterion of the limiting electric field intensity that proves to be a reasonably efficient tool of modeling and prediction of the electric strength:

$$E(t) \ge E_c \tag{2}$$

where E_c is the critical intensity, which can depend on many material and geometrical factors including the interelectrode distance, and *t* is the time. Under a fast increase in the applied voltage, which is inherent for pulse modes, the experimentally determined critical values of fields are characterized by a strong time dependence and, as