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Fracture in heterogeneous materials: experimental and theoretical studies

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Abstract

The kinetics of fracture in stressed heterogeneous materials is investigated in a differentiated way using the parameter Δ*t*, the interval between single or multiple (cooperative) microfracture events recorded by acoustic emission (AE) responses. The patterns of fracture nucleation and growth, which is a statistic process, are controlled by the heterogeneity of deforming material. There are two important aspects revealed by the study: 1) structural heterogeneity of materials causes uneven distribution of stress in loaded solids and thus creates local zones of microstress and ensuing microfracture in the overstressed zones; 2) AE measurements and microseismic monitoring are applicable to prediction of fracture by locating its source and thus allows predicting related hazard in mines, tunnels, bridges, nuclear-power plants, and other important engineering objects.

Keywords: zone of brittle failure; fracture; prediction; acoustic emission; fracture source; microseismic monitoring

Introduction

Fracture in heterogeneous materials is quite a complex phenomenon, and its different elements have been largely studied (Adushkin et al., 2007; Guglielmi et al., 2014; Kuksenko et al., 2014; Lukichev et al., 2015; Makhmudov and Kuksenko, 2005; Nosov and Lavrin, 2012; Oparin et al., 2015; Potanina et al., 2015; Shcherbakov and Chmel, 2014; Smirnov and Ponomarev, 2004; Sobolev et al., 2015; Soloviev and Spivak, 2009; Vikulin et al., 2016), at atomic through macroscopic scales (Ammon et al., 2008; Baddari et al., 2012; Beeler, 2004; Cai and Liu, 2009; Chen et al., 1993; Corrêa and Nascimento, 2005; Dresen et al., 2010; Gezalov et al., 1969; Kuksenko et al., 2009; Nosov and Burakov, 2004; Nosov and Elchaninov, 2011; Petrov, 1983; Ponomarev et al., 1997; Sadovsky et al., 1987; Smirnov and Ponomarev, 2004; Xing et al., 2004; Zhurkov et al., 1981).

Failure in solids is a thermoactivation process (Makhmudov, 2011; Regel et al., 1974; Zhurkov, 1968) driven by nucleation and growth of microfractures (Gezalov, 1969; Leskovsky et al., 2013; Shcherbakov et al., 2013). Experimental investigation of fracturing, which was applied first to polymer materials, revealed two stages of the process (Petrov, 1983; Zhurkov et al., 1981): (i) first single stable fractures form randomly throughout the solid volume and their clustering leads to the formation of a fracture source; (ii) then strain localized at the source propagates and produces a major fracture leading eventually to failure (Kuksenko et al., 2007, 2010; Tamuzh and Kuksenko, 1978). Fracturing is commonly studied in an integrated way (Baikova et al., 2008; Stavrogin and Protosenya, 1992) as some number of fractures formed over a period of time, while individual fractures and the discrete character of fracture events remain overlooked. Meanwhile, the method of acoustic emission (AE) is free from this drawback (Kuksenko et al., 1985; Lockner et al., 1986; Simpson et al., 1988; Stanchits et al., 2003) and allows picking the time when each *i*th microfracture originates (t_i) and the parameters (e.g., amplitude A_i and duration T_i) of acoustic responses to its formation. With this basic advantage, the method it applicable to investigate the kinetics of microfracturing in a differentiated way (Lockner and Stanchits, 2002; Mansurov et al., 2009; Shapiro et al., 2002; Stanchits et al., 2006; Utsu et al., 1995; Vinciguerra et al., 2005; Wan et al., 2009; Wang et al., 2011).

Methods

The system of AE monitoring used in the reported experiments provides real-time measurements of the amplitudes and arrival times of each acoustic response to deformation which

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exceeds the chosen discrimination limit. Waves travel from the source to one or several transducers where acoustic energy converts to electric energy. The electric signals are recorded by an *A-Line 32D (PCI-8E)* AE measurement system (Makhmudov, 2012) and displayed as oscillograms, possible source locations, and digital indications which provide information on the state and behavior of stressed materials and allows detecting and locating their defects (structural health monitoring). Piezoelectric transducers (sensors 1 and 2) of the domestic design, with a transmission band from 5 MHz to 100 kHz, were mounted on the lateral surface of a sample or inside the strain unit. The acoustic responses of a loaded sample reached the sensor, became converted into electric signals and amplified, and then recorded by the *A-Line 32D (PCI-8E)* system as standard signals with their amplitudes and durations proportional to the amplitude and duration of the envelope of acoustic waves. Then the standard signals arrived at the amplitude and time signal analyzer coders, became digitized as 12-bit binary codes, and were forwarded to PC for analysis and storage. As a result, information for each acoustic response included its arrival time, amplitude, and envelope duration (Fig. 1).

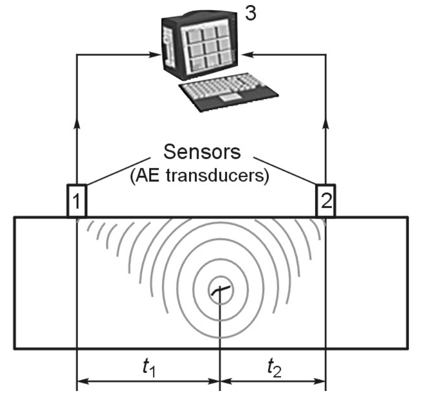

Fig. 1. Automated statistical data processing. 1, AE transducer (sensor 1); 2, AE transducer (sensor 2); 3, PC-based central unit for data acquisition and processing; 4, sample; t_1 and t_2 are the arrival times of acoustic waves to sensors 1 and 2, respectively.

The samples were composite materials of two types: porous glass (*porosital*) and unidirectional organic fiber-reinforced plastics (OFRP). Porous glass is a model composite with a glass matrix enclosing pores spaced at 0.1 mm on average (at distances commensurate with their diameter). The breakdown of a link between two next pores corresponds to a single failure event in samples subject to uniaxial compression. Loading of OFRP samples was by uniaxial tension. Single failure events in that case consisted in rupture of reinforcing fiber or its separation from the matrix. Strain rates were constant in both cases. The acoustic responses were strong enough to be recorded by the piezoelectric transducers.

Results and discussion

The kinetics of fracturing shows statistical behavior as the time interval Δt between two successive microfracture events turns out to be a random value (see Fig. 2 for the Δt pattern in the beginning of loading).

The distribution of Fig. 2 is exponential at not very small Δt, which can be demonstrated in a graphic way in semilog coordinates. This Δt pattern could be expected from general considerations. Indeed, let a loaded solid contain Q microscopic elements with the function of their life-time $p(t)$ meaning that of these elements break down by the time t. The next element breaks down within the interval t, $t + \Delta t$, where Δt is a random value, with its distribution function $f_t(t)$. Obviously, the $f_t(\Delta t) = 1 - \chi_t(\Delta t)$, where $\chi_t(\Delta t)$ is the probability that the interval between two successive microfracture events may exceed Δt. This probability equals the probability that none of the elements breaks down in the interval t, $t + \Delta t$, that is

$$\chi_t(\Delta t) = [1 - \Delta p(t, \Delta t)]^{Q-q};$$

$$\Delta p(t, \Delta t) = p(t + \Delta t) - p(t) = \int_t^{t+\Delta t} \dot{p}(t')\,dt' = \dot{p}(t^*)\,\Delta t,$$

$t < t^* < t + \Delta t$, at small Δp and large $Q - q$. Taking into account the definition of e (base of the natural logarithm),

$$\lim_{n\to\infty}\left(1 + \frac{a}{x}\right)^x = e^{-a}$$

asymptotically $\chi = \exp(Q - q)\Delta p$,

wherefrom $f_t(\Delta t) = 1 - \exp Q[1 - p(t)]\dot{p}(t^*)\,\Delta t$.

In the case of small $p \ll 1$, the function finally is

$$f_t(\Delta t) = 1 - \exp(-\Delta t/\overline{\Delta t});\ \overline{\Delta t} = 1/Q\dot{p}(t^*). \qquad (1)$$

Thus, the distribution of the time intervals Δt between two successive single microfracture events is exponential. The function $p(t)$ is controlled by the statistics of intervals between destructive thermal fluctuations in loaded solids at a constant stress growth rate $\dot{\sigma}$, at $p \ll 1$, is (Petrov and Gorobei, 1978)

$$p(t) = \frac{\tau}{\theta_0}\left(e^{1/\tau} - 1\right);\ \tau = \frac{kT^0}{\gamma\dot{\sigma}};\ \theta_0 = \tau_0 \exp\frac{U_0}{kT^0},$$

where τ_0, U_0, and γ are the parameters of Zhurkov's equation (Zhurkov, 1968), T °C is the absolute temperature; k is the Boltzmann constant. Therefore, at the initial stage,

$$\dot{p}(t < \tau) = \frac{1}{\theta_0},$$

i.e., the process is stationary (in distribution (1), average $\overline{\Delta t}$ and other variables are independent of time). At long times,

$$\dot{p}(t > \tau) = \frac{1}{\theta_0}e^{t/\tau}$$

nucleation of microfractures becomes non-stationary.

In order to find the causes of deviation from the exponential trend (Fig. 2), for small Δt, consider the spectra of acoustic responses, with their amplitudes A and durations T (Fig. 3).