Local stress fields in solids estimated by acoustical emission method

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Abstract. Based on the Zhurkov’s kinetic concept of solids’ fracture a local internal stress estimation method is introduced. Stress field is computed from the time series of acoustic emission intervals between successive signals. For the case of two structurally different materials the time evolution of these stresses is examined. It is shown that temporal changes of these stresses’ accumulation law may serve as a precursor of incoming macroscopic fracture.

1. Introduction

The knowledge of the stress fields acting in situ in materials appears to be of an exceptional importance since it is useful not only in understanding the fracture process itself but also to provide exploitation safety of constructions made of these materials. Using acoustic emission (AE) data one may obtain the needed information analyzing time intervals between successive AE events (pauses between them).

According to the kinetic concept of strength (S.N. Zhurkov [1]) the fracture process may be treated as a sequence of elementary events caused by thermal fluctuations. The mean expectation time of such fluctuations is determined by Zhurkov’s formula:

$$\tau = \tau_0 \cdot \exp \left( \frac{U_0 - \gamma \sigma}{kT} \right); \quad (1)$$

where $U_0$ is the process activation energy, $\tau_0$ is the characteristic time of atomic thermal vibrations, $\sigma$ is the applied external stress, $k$ is the Boltzmann constant, and $T$ is the absolute temperature. Both $U_0$ and $\tau_0$ are considered here as materials constants. The value $\gamma$ is called the activation volume. Most often it is interpreted as a product of the atomic volume by the local stress multiplier [2].

We assume that in the absence of external stress the material stays in the equilibrium state. Under the external stress this state is no longer the equilibrium one, so the system passes a set of metastable states in order to find a new equilibrium. The lifetime of the system in each of this state $i$ is $\Delta t_i$, and can be treated from AE time series as the pause between two successive AE events (signals). The acoustic event appears as the result of material restructuring such as twinning, crack formation or growth [3–5]. The transition to the next metastable state is caused by thermal fluctuation according to the Zhurkov’s law (1) but it happens locally in the particular region of the sample at a certain time, so the value of $\sigma$ is a function of these parameters: $\sigma = \sigma(\vec{r},t)$. We assume $\gamma$ to be a scalar, so the value $\sigma$ must be scalar too. In general several components of the stress tensor might be present in the fracture point. The simplest scalar value of the stress tensor is its first invariant, so we assume that it’s just this invariant appears in (1). Taking this into account we rewrite expression (1) as follows:
\[ \sigma(\vec{r}, t_i) = \frac{U_0}{\gamma} + k \cdot T \cdot \ln \left( \frac{\tau_0}{\Delta t_i} \right) \] (2)

and consider \( \gamma \) as the constant of material. Note that the local stress can be determined with the known values of \( \Delta t_i \) (the pause between AE signals) and temperature \( T \). In general this local temperature might differ from the mean temperature of the sample due to the release of the elastic energy in the neighborhood, but this change occurs after the elementary Arrhenius event takes place. Therefore, the temperature in (2) is assumed to be constant.

Note that the dependence of the stress on AE pause is logarithmic. As far as the measurement accuracy of the pause is of about \( 10^{-5} \) s it is too poor for obtaining of any reliable value of \( \sigma \). However, we are interested not in the value itself but rather its variation in time.

2. Experimental

The following materials were studied: considerably inhomogeneous and practically pore-free Westerly granite [6], with the average grain size of 75 \( \mu \)m [7], and a brittle sedimentary rock Berea sandstone, with an average grain size of 20 \( \mu \)m and porosity of about 15–20\% [8]. Two AE105A wideband piezotransducers with a bandwidth of 450–1150 kHz were attached to the sample ends. Experimental time series contained several tens of thousands of the located signals.

Cylindrical samples with diameter \( d = 10 \) mm and height \( h = 20 \) mm were subjected to uniaxial quasi-static compression at a constant displacement rate of 5 \( \mu \)m/min. The mechanical stress was applied parallel to the axis of the cylinder. This compression was applied up to the force equal to 0.9 of \( F_{\text{max}} \) (\( F_{\text{max}} \) is the fracture load determined in preliminary experiments). Next, the sample was kept at a constant strain until the AE activity dropped to zero. As a result a main crack was formed on the one hand, and, on the other hand the integrity of the sample was retained.

Figure 1 shows the typical time dependencies of the strain and AE activity (the number of signals per unit time). Clearly, the AE activity considerably increases by approaching the maximum strain and then (by keeping the constant strain) drops to zero.

![Figure 1](image)

**Figure 1.** Variations of the strain (dashed curve) and acoustic emission activity (solid curve) during the experiment in (a) Berea sandstone and (b) Westerly granite.

The X-ray microcomputed tomography of the samples with the spatial resolution of 3 \( \mu \)m was implemented before mechanical tests. The samples selected were without any structural anomalies, which can act as the stress concentrators and sources of the damage accumulation.

The real time recording of the AE signals was implemented while loading of the sample. Two piezoelectric transducers were mounted to the sample ends that allowed us to solve the problem of the linear location of the AE signal sources. Each AE signal was characterized by the emission time, the
source coordinate over the sample height, and the energy. The accuracy of determining the AE signal source coordinates was of about 1.5 mm. Details of the experiment were described previously, for instance, in [9].

It should be noted that in any AE experiment, not all AE signals are recorded, but only some of them (this is determined by the apparatus capabilities). In this case, the direct application of the expression (2) is impossible, since recorded pause $\Delta t_i$ can consist of several shorter intervals, which contain missing signals:

$$\Delta t_i = \sum_j \Delta t_{ij} = \tau_0 \cdot \exp \left( \frac{U_0}{kT} \right) \cdot \sum_j \exp \left( -\frac{\gamma \cdot \sigma_{ij}}{kT} \right)$$

(3)

Each of these shorter intervals $\Delta t_{ij}$ is described by the expression like (1), but in general, the sum of exponents is not an exponent itself. In our case, however, AE emission occurs at large applied stresses and, consequently, at high internal local stresses, for which $\gamma \cdot \sigma_{ij}/kT >> 1$. Then, in sum (3) only one exponent with the minimum stress is predominant, since the remainder decay even faster. Therefore, in this case sum (3) can be replaced by one exponent. The estimate of stresses obtained by the considered method is the lower bound of the stress estimation. The limited accuracy of the AE events times’ determination leads to the same result.

3. Main results.

AE data time series were divided into non-overlapping sequences of 256 events. Samples were divided into regions with the height of 2 mm, so each event of the sequence fell into one of these areas. For each region mean values of $\sigma(h,t)$ with respect to the time sequence were computed ($t$ is the last time of the time sequence). Some of them are presented in figure 2. We used the following values for material constants: $U_0 = 160 kJ/mol$, $\gamma = 1 kJ/mol \cdot MPa$, and $\tau = 10^{-13} s^{-1}$ [10].

![Figure 2. Time dependence of local stress: (a) Berea sandstone, (b) Westerly granite](image)

The characteristic feature of these plots is a considerable increase of the stress (the time stress concentration) in the periods of the maximum AE activity for Berea sandstone. It is not surprising, since in this work the stress values are exactly determined from this activity. Away from these periods local stress decreases for Berea sandstone and increases for Westerly granite. This indicates the possibility of stress relaxation in the sandstone as well the lack of it in the granite. Mention that the variation of the local stresses in different areas of the sandstone is much higher than that in the granite.

Next difference between the fracture process of Berea sandstone and Westerly granite is the fact that in the sandstone the fracture is concentrated in one or two centers, while in granite the number of
these centers is significantly higher. It is proved by plotting the space distribution histograms of acoustic events versus height of the sample (not shown here).

The time dependencies of the $\sigma$ value in these centers are presented in figure 3. One can notice that while approaching the fracture moment the character of these curves changes significantly. Instead of decrease $\sigma$ increases in the case of the sandstone, while for granite the increase of $\sigma$ becomes larger.

![Figure 3. Local stress dependence in the fracture centre of Berea sandstone (a) and Westerly granite (b) (two centers)](image)

4. Discussion.

The difference in structure of materials under investigation leads to their different behavior during the fracture process. Observed relaxation of mechanical stresses in the sandstone might be connected with the pore closure under the external load, while the lack of these pores makes this kind of relaxation impossible in the granite. Instead, internal stresses accumulate in this case. Strong heterogeneity of the granite causes the existence of multiple fracture centers in this material, while the homogeneity of the sandstone leads to a more localized fracture process. Such a behavior was previously predicted in the cellular automata model. [11].

Temporal changes of the stress relaxation may serve as the precursor of incoming macroscopic fracture. For the sandstone it might be the impossibility of further stress relaxation and transformation to their growth (figure 3a) while in granite the acceleration in the stress accumulation indicates the approach of the material destruction (figure 3b).

Noteworthy that heterogeneity of granite leads to the weak dependence of the stress space distribution on the height of the sample which corresponds to multiple destruction (figure 2b), while in the sandstone this distribution is highly inhomogeneous having maximum values in the centers of fracture (figure 2a). Thus, the structural heterogeneity leads to the stress homogeneity and vice versa.

5. Conclusion

The proposed method for calculating local internal stresses based on the kinetic concept of strength by S.N. Zhurkov seems to be effective for these stresses’ estimation in situ using the acoustic emission technique. Changes in the character of the stress temporal relaxation may serve as a precursor for macroscopic destruction of material.

References

[1] Zhurkov S N 1965 Int. J. Fracture Mechanics 1 311–23
[2] Regel’ V R, Slutsker A I and Tomashevskii E E 1974 Kinetical nature of the strength of solid bodies. (Moscow: Nauka) p 560
[3] Vettegren’ V I, Kuksenko V S and Shcherbakov I P 2013 Tech. Phys. 58 136–9
[4] Goebel T H W, Becker T W, Schorlemmer D, Stanchits S, Sammis C, Rybacki E, ad G. Dresen
G 2012 Journal of Geophysical Research 117 B03310
[5] Xinglin Lei and Shengli Ma 2014 Earthquake Science 27 627–46
[6] Chayes F 1950 Am. J. Sci. 248 378–408
[7] Stesky R M 1978 Can. J. Earth. Sci. 15 361–375
[8] Churcher P, French P and Shaw J 1991 Proc. SPE International Symposium on Oilfield Chemistry (Anaheim, California) (Society of Petroleum) SPE21044
[9] Damaskinskaya E E, Hilarov V. L, Panteleev I A, Gafurova D. R and Frolov D. I 2018 Phys. Solid State 60 1821–6
[10] Efimov V P 2006 Fiz.-Tekh. Probl. Razrab. Polez. Iskop No. 3, 11–17
[11] Hilarov V L 2011 Phys. Solid State 53 758–62