In-situ estimation of defect volume from parameters of acoustic emission signals

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Abstract. By using two methods of nondestructive testing, i.e., acoustic emission (AE) measurements and X-ray computed microtomography (CT), an experimental study of defect accumulation during a uniaxial compression of a natural heterogeneous material was carried out. A joint analysis of the AE and CT data revealed a correspondence between energy characteristics of the acoustic emission accompanying defect formation and volume of defects. It is shown that the dependence of the total energy of AE signals on the defect volume is linear, which is consistent with the phenomenological dependences for earthquake focuses obtained earlier. The linear dependence was used to estimate the average defect size. It is shown that, regardless of the assumed defect shape, its average linear size does not exceed 100 µm.

1. Introduction
The formation and evolution of a defect structure (cracks) in the volume of a heterogeneous material under the action of mechanical stresses leads to a release of thermal, acoustic, and electromagnetic energies [1-4]. The predominant mechanism in the case of quasi-static deformation of brittle heterogeneous materials is the generation of elastic waves (acoustic emission) that accompanies the formation and development of submicro-, micro- and macrocracks. However, the relation between parameters of AE signals and signal source, i.e., defect, has not been clearly understood until now.

The goal of our study was to reveal the relation between parameters of the acoustic emission recorded during a quasi-static compression of a natural heterogeneous material and its defect structure.

The experimental study of the defect structure evolution involved the use of two independent methods, i.e., acoustic emission (AE) measurements and X-ray computed tomography (CT).

2. Experimental
Cylindrical samples (d=10mm, h=20mm) made of a natural heterogeneous material (Berea sandstone) were subjected to uniaxial quasi-static compression. The Berea sandstone is a brittle sedimentary rock consisting mainly of quartz grains with a characteristic size of ≈20 µm [5]. The quasi-static testing of samples was carried out under uniaxial compression by using a AGX-Plus (Shimadzu, Japan) electromechanical machine with a maximum force of 30 tons. The load was applied parallel to the
cylinder axis. At the first stage the load was increased by displacing the loading plates at a loading rate of 5 µm/min. The compression limit was taken to be a force equal to 0.9 of $F_{\text{max}}$ ($F_{\text{max}}$ is the breakdown load determined in preliminary experiments). Then the sample deformation was kept constant until the AE activity dropped to zero.

The formation and development of defects in the process of sample loading were controlled by recording acoustic emission signals in real time with an Amsy-5 Vallen system (Germany). Two piezoelectric AE105A transducers (operating frequency range 450-1150 kHz) were attached to special hollow cylindrical plates with the help of which the sample was directly loaded. Each acoustic emission signal was characterized by the radiation time, source coordinate along the sample height, and energy. The accuracy with which the coordinates of the AE signal source was determined was about 1.5 mm. Seven samples were tested. In each experiment, about 20,000 AE signals were recorded, which was sufficient for statistical processing.

To study the defect structure of the samples, we used a SkyScan 1172 tomograph (Bruker, Belgium) equipped with a Hamamatsu 100/250 microfocus X-ray tube with a focal spot of 5 µm and a 11 Mpx detector. The selected sample shape and size made it possible to achieve a spatial resolution of computed tomography of ~3 µm, which was the maximum possible resolution for the samples of the size used (d=10 mm, h=20 mm) because of the physical principles of tomography and design features of the X-ray tube and tomograph camera [6].

The samples were scanned before and after mechanical tests. The entire batch of sandstone samples was scanned prior to testing. For further experiments, we selected the samples which had no structural anomalies that could become stress concentrators and sources of fracture.

3. Results and Discussion

Figure 1 shows typical time dependences of deformation, AE activity (number of signals per unit time), and energy of acoustic emission signals. It can be seen that the acoustic emission activity increases significantly when the maximum deformation is approached, and at the second stage of deformation (deformation is constant) it decreases with time to zero.

![Figure 1](image)

**Figure. 1.** Changes in deformation (black line), acoustic emission activity (blue line), and energy of individual AE signals (gray points) during the experiment.

The energy distribution of all AE signals has a power-law form $\frac{\Delta N}{\Delta E} = aE^{-b}$ (with the coefficient of determination $R^2=0.95$) (Figure 2). This result corresponds to the earlier finding [7, 8] that the energy distribution of AE signals has an exponential form and corresponds to a nondangerous stage of defect
accumulation under stresses of up to ≈0.8 - 0.9 \( \sigma_{\text{destruction}} \) (\( \sigma_{\text{destruction}} \) is the breaking stress). At a stress of 0.8 - 0.9 \( \sigma_{\text{destruction}} \), a change in the functional form of the distribution from an exponential to a power-law one is observed, which is an indicator of the onset of the critical (“dangerous”) stage of defect formation. This suggests that the defect formation process in our experiment corresponded to a dangerous stage, during which the main crack formation occurred.

![Figure 2](image2.png)

**Figure 2.** Energy distribution of AE signals recorded during loading.

A tomographic survey of a sandstone sample after the experiment showed that loading resulted in formation of a main crack oriented at a certain angle relative to the load axis (Figure 3). Note that no defects were found outside the main crack region. The same result was obtained earlier [9] in the investigations of defect accumulation in other natural heterogeneous materials, i.e., Westerly granite and metasandstone. This indicates that the results are general and valid for all the materials we studied.

![Figure 3](image3.png)

**Figure 3.** Three-dimensional visualization of the defect structure built from X-ray tomographic data by using specialized CTan and CTvol software.

In order to exclude the influence of end effects, only the height interval from 4 to 14 mm was considered in further analysis of tomographic and acoustic emission data. The use of two methods of non-destructive testing allowed us to compare the dependences of the signal energy \( E_{\text{total}} \) and volume of
defects on the coordinate (Figure 4). The volume of defects was calculated on the basis of X-ray computed tomographic data by using a specialized CTan software in layers with a height of 2 mm. The total energy of the AE signals was calculated for each layer. Figure 4 shows that the dependences are similar.

![Figure 4](image_url)

**Figure 4.** Variations in total energy of AE signals (curve 1) and volume of defects (curve 2) along the coordinate (sample height).

The results obtained allowed us to reveal a relation between the total AE energy \( E_{\text{total}} \) and the volume of defects (Figure 5). The approximation shows that the dependence is linear (with a coefficient of determination \( R^2 \approx 0.98 \)) and has the form

\[
E_{\text{total}} = 0.62V - 0.15
\]  

(1)

A similar dependence for geological scales was obtained by Academician Sadovsky [10] in the middle of the last century. It was shown that the energy released during an earthquake was directly proportional to the volume of the earthquake focus. However, it was impossible to obtain such a dependence in laboratory experiments earlier.

![Figure 5](image_url)

**Figure 5.** Relationship between total energy of AE signals and volume of defects.
Note that the volume of defects in a layer is an integral characteristic. To estimate the volume of an individual defect-source of the AE signal, it is necessary to perform normalization to the number of signals. Then the average defect volume is $\sim 10^{-4} - 10^{-5}$ mm$^3$.

The results of computed tomography and acoustic emission data can be used to estimate the characteristic linear size of single defects formed during sample deformation. Such an estimate requires an a priori hypothesis about the shape of the defects formed. Following [11-14], we assume that the defects are in the form of a

- a sphere with diameter $D_1 = \frac{3}{\sqrt{\pi}} V^{\frac{1}{3}}$;

- an elongated ellipsoid with equal middle and semi-minor axes ($b$) and the longest semi-axis $D_2 = \frac{3V}{4\pi b^2}$; and

- a circular crack with diameter $D_3 = \frac{4V}{\pi h}$, where $h$ is the crack thickness.

To calculate the characteristic linear size for the case of an elongated ellipsoid and a circular crack, we assume that the dimensions $b$ and $h$ are half the maximum semi-axis and thickness. Let us estimate the characteristic linear size from the total volume of all the defects formed $V_{total}$ normalized to the number of AE signals and the total energy of these signals. As a result, we obtain the following characteristic sizes for defects of various shapes

$$D_1 \approx 88 \mu m,$$

$$D_2 \approx 69 \mu m,$$

$$D_3 \approx 97 \mu m,$$

which differ by no more than 30% from each other. Thus, regardless of the hypothesis about the characteristic shape of the AE source, its average linear size does not exceed 100 µm.

4. Conclusion

The experimental study of the defect accumulation patterns in Berea sandstone samples under uniaxial compression was carried out. Analysis of the data on the internal structure of sandstone after deformation obtained by X-ray computed tomography showed that all defects were localized in the region of the main crack.

The use of two independent methods, i.e., acoustic emission measurements and X-ray computed tomography, made it possible to compare the spatial distributions of the volume of microdefects and the total AE signal energy. It was found that there was a linear relationship between these parameters (it was impossible to find such a relationship earlier in laboratory experiments).

The result obtained in our studies has a significant applied value. Characteristic dimensions of defects formed during operation of a test object can be estimated in situ from the energy of the recorded acoustic emission signals.

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