Evolution of defect structure and indicator of transition to critical state of material

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Abstract. A feature that allows one to estimate the degree of criticality of the state of the material subjected to the mechanical load has been identified. Two independent non-destructive methods, i.e., acoustic emission (AE) and X-ray computed microtomography (CT), were used at each stage of sample loading. It was found that the energy distribution of AE signals did not always obey the Gutenberg-Richter law. It was also found that the type of energy distribution of AE signals could be used as an indicator of the state of a deformed material. The exponential function pointed to a non-critical state; the power-law function indicated that the damage accumulation process had passed to the “dangerous” stage. This feature can be used as a physical basis for a new method of non-destructive testing which will allow one to reveal “dangerous” (requiring replacement or repair) spatial regions of objects (constructions, pipelines, etc.).

1. Introduction

Prediction of destruction of natural and man-made objects is one of the most important problems of physics and mechanics of strength, which still remains unresolved. Experimental evidence shows that the defects accumulation in heterogeneous materials under mechanical load is a complex multistage process. At the early stages of loading, the formation of defects distributed randomly throughout the entire volume of the deformed material occurs. Then defects are localized in a certain spatial region, i.e., a fracture nucleation site is formed. The search (see theoretical [1,2] and experimental [3,4] papers) for prognostic universal reliable criterion for the transition from the stage of disperse defect accumulation to the stage of a fracture nucleation site formation has not succeeded.

A loaded solid as a nonlinear inhomogeneous system [5] with positive feedback can be both in a stable (“non-dangerous”) state resulting from an effective dissipation of the energy supplied to the solid and in a metastable (“dangerous”) state in which a small disturbance can lead to a global loss of stability and subsequent macro-destruction. The goal of our studies was to seek for indicators of the critical (metastable) state of the material. From the point of view of the defect system of a deformed solid, the non-dangerous state means that the formation of new defects does not lead to the material strength loss. The dangerous state means that a localized defect structure, the avalanche-like development of which will inevitably lead to a catastrophic destruction, has been formed.

To solve the problem, the approach based on the concept of self-organized criticality was used [6].
We assume that the set of defects that are formed at early stages of deformation under load much smaller than destructive ones can be regarded as a memoryless system. This means that the state of the system does not depend on its history and is determined only by the state at the particular time moment. Thus, this is the Markov process [7], i.e., a random process that can predict future independently from the past. The Markov process is described by the exponential distribution of its parameters.

In our study, the system parameter of interest will be the energy of AE signals resulting from defects formation. Then the energy distribution of the AE signals at this stage of deformation should be exponential.

As the load increases (as the final stage of deformation is approached), the set of defects passes into the state of self-organized criticality in which a small disturbance can lead to a catastrophe. This state has the property of space-time invariance and is described by power-law distribution of parameters. Consequently, the energy distribution of the AE signals at this stage of deformation should be a power-law one.

In order to verify our hypothesis, experiments on deformation of heterogeneous materials had been carried out. The object of our studies was Westerly granite [8]. A series of tests was carried out (11 samples). Further, by using one experiment as an example, general results will be demonstrated.

Two independent non-destructive methods, i.e., acoustic emission (AE) and X-ray computed microtomography (CT) were used at each stage of deformation of the same sample. This allowed us to control the evolution of the defect structure and to compare it with the parameters of the AE signals.

2. Experimental

The quasi-static testing of samples of Westerly granite was carried out under uniaxial compression by using a Shimadzu AGX-Plus electromechanical machine with a maximum force of 30 tons.

To carry out a real-time monitoring of the acoustic emission during deformation, an Amsy-5 Vallen-Systeme (Germany) apparatus was used. Two AE105A wideband piezotransducers with a bandwidth of 450–1150 kHz were attached to the sample ends. Each acoustic emission signal was characterized by the emission time, coordinate, and energy. The accuracy of the acoustic emission source localization was approximately 2 mm.

The X-ray tomographic study of the defect structure of the rock samples before and after mechanical tests was carried out by using a ScyScan 1172 tomograph (Brucker, Belgium) equipped with a Hamamatsu 100/250 microfocus X-ray tube and 11 Megapixels detector panel. Scanning parameters were: voltage 70 kV, current 129 μA, distance from the source to the camera (detector) =213.580 mm, distance from the source to the object =75.030 mm. The rotation step was 0.200 deg, the exposure time was 3770 ms, and the scan duration was about 24 hours.

The shapes and dimensions of the samples optimal for both mechanical tests and tomography were found. They were cylinders with a diameter of 10 mm and a height of 20 mm. The experiments were carried out on Westerly granite samples with the average grain size of 0.075 mm [8]. The spatial resolution of tomographic images with this sample geometry was ~ 3 μm. The achieved resolution was the best possible for the samples of this size [9], taking into account the physical principles and engineering features of the X-ray tube and tomograph chamber.

A tomographic survey of all samples was carried out before the mechanical tests. We selected the samples without structural anomalies which could become stress concentrators and sources of damage accumulation.

The sample was deformed in several stages. At each stage the load was slowly increased (at a rate of ≈5 N/s) to a certain magnitude F. Then the sample was kept under this load F until the activity of the acoustic emission signals fell to zero (Figure 1a). Then the sample was unloaded, and a tomographic survey was carried out. At the next stage the load F was increased by 0.08Fmax, where Fmax is a breakdown force. The experiment had stopped when an avalanche-like increase in the activity of acoustic emission began (Figure 1b). This indicated that the sample breakdown was approaching. As a result, the sample preserved its integrity. Tomographic survey was performed after each stage. All in all, 11 stages of loading and 11 tomographic surveys were performed.
3. Results and discussion

We analyzed the energy distribution of the AE signals. Figure 2 shows the total energy distribution of AE signals at early stages of loading. It is clearly seen that the data are approximated by a straight line in semi-logarithmic coordinates. Hence, the distribution is exponential at this stage of loading.

This means that the energy distribution may differ from the power-law one predicted by the Guttenberg-Richter law [10].

\[
\frac{\Delta N}{\Delta E} \sim \exp\left(-\frac{E}{E_0}\right)
\]

Figure 2. Early stages of loading: a – energy distribution of AE signals; b – 3D visualization of cracks

Three-dimensional visualization of cracks based on CT data is shown in Figure 2b. These are the cracks formed after all the early stages of loading. It is seen that the cracks are distributed randomly, localization is not observed.

Thus, the disperse defect accumulation corresponds to the exponential energy distribution of AE signals.
A computer simulation of local stresses arising in a loaded material with defects [11] was carried out. Location and sizes of defects were similar to those revealed by computed tomography. It was shown that local stresses were insufficiently high to cause the growth of defects. The formation of new defects does not change the pattern of stress distribution in the bulk of the material. This let us suggest that the material may be under load for a long time. This is the non-dangerous state of the material.

Let us consider in detail the acoustic emission data obtained at the last (pre-destructive) stage of loading. A spatial "scanning" of the sample was carried out. To this end, a spatial region of the sample was selected, and the energy distribution for the signals detected only from this region was built. Then the procedure was repeated for another region. As a result, the area (Region A in Figure 3b) the distributions for which were approximated by an exponential function (Figure 3a) and the area (Region B in Figure 3b) the distributions for which were approximated by a power-law function (Figure 3c) were revealed.

\[
\frac{\Delta N}{\Delta E} \sim \exp\left(-\frac{E}{E_0}\right)
\]

\[
\frac{\Delta N}{\Delta E} \sim E^b
\]

Figure 3. Pre-destructive stage of loading: a – energy distribution of AE signals (Region A – “non-dangerous”); b – defect structure; c – energy distribution of AE signals (Region B – “dangerous”)

The power-law type of energy distribution of AE signals indicates that a set of defects has passed into the state of self-organized criticality, i.e., the material is in a dangerous state.

Let us compare this result with the data of X-ray tomography. Figure 3b shows three-dimensional visualization of defects in the sample at the pre-destructive loading stage. It can be seen that region B of the sample is characterized by a growing concentration of cracks and formation of a fracture nucleation site, while in region A the cracks are distributed randomly.

According to our hypothesis, this means that in one region of the sample the state of the material is still not dangerous, while in another region the material is in a dangerous state.

The functional type of the energy distribution of AE signals allowed us to identify the “non-dangerous” and “dangerous” regions of the sample.

4. Conclusions

It has been found that the energy distribution of AE signals is not always described by a power-law function, as was assumed previously. A deviation from the Guttenberg-Richter law is sometimes observed.
It has also been found that the type of energy distribution of AE signals can be used as an indicator of the deformed material state and criterion for the transition of fracture to a dangerous state.

The exponential function indicates the stable (“non-dangerous”) state of the deformed material.

The power-law function indicates that the damage accumulation process has passed to a “dangerous” stage.

This result can be a physical basis for the new method of non-destructive testing.

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