Damage initiation in brittle and ductile materials as revealed from a fractoluminescence study

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ABSTRACT. A set of heterogeneous and homogeneous materials differing in their brittle and ductile characteristics (granite, marble, silica ceramics, silicon carbide, organic glass) were subjected to impact damaging by a falling weight. Multiple chemical bond ruptures produced by elastic waves propagating from a damaged zone were accompanied by the photon emission generated throughout the sample (tribo- or fractoluminescence, FL). The statistical analysis of the FL time series detected with high resolution (10 ns) showed that the energy release distributions in brittle solids follow the power law typical for the correlated nucleation of primary defects. At the same time, the formation of damaged sites in ductile materials (marble and organic glass) was found to be fully random.

KEYWORDS. Impact fracture; Fractoluminescence; Time series; Random statistics; Correlated statistics.

INTRODUCTION

A loaded body is open thermodynamic system, in which along with non-reversible changes, such as ruptures of structural links, the self-organizing of the ensemble of newly-formed defects proceeds with maintaining the metastable (critical) state of the stressed structure. An origin of self-organizing is so-called long-range interactions between initial damages when these ones affect each other at distances exceeding the radius of a damaged site. In contrast to short-range cross-feed in equilibrium (unloaded) structures, which decay exponentially with distance, the power law dependence of the energy release on damage size (scaling) manifests itself under conditions of the external energy income. Thus, the scaling phenomena occur over an area much greater than is predicted by elasto-dynamic interactions [1].
As far as multiple interactions implies the abundance of damaged sites, the scaling effect during straining and fracturing is inherent in heterogeneous materials, such as building materials [2], ceramics [3], composites [4], rocks [5], etc., in which the multi-site damaging takes place. Fractured brittle homogeneous solids exhibit this phenomenon only at the macroscopic scale level – when the number of fragments of a broken body reaches the statistical significance [6]. At the same time, even conventionally homogeneous materials display pronounced heterogeneity at the nanostructural scale level. Therefore, the scaling effect could manifest itself during the primary defect accumulation even in structurally-ordered materials. This scale level is available for studying with the help of the fractoluminescence technique, which is sensitive to the nanostructural degradation in stressed solids [7]. Chemical bond breakage is accompanied by the photon emission from reconfiguring electronic structures. Amplitudes of light pulses are proportional to quantity of counted photons, and, correspondingly, to the energy released in events of primary damage nucleation.

A historical term for the light emission from mechanically treated solids is "triboluminescence"; however, in recent decades the definition of the effect has been subject to some refinement. The term "triboluminescence" is commonly referred to the light generated through rubbing a material, while the photon emission from deformed or fractured solids is more frequently called "mechanoluminescence". Kawaguchi [8] introduced a narrower term "fractoluminescence" (FL) to stress the difference between the strain- and fracture-induced effects. The latter term seems to be mostly adequate to experiments presented in this communication.
In this work, five materials substantially differing in their physical and mechanical characteristics (heterogeneous brittle and ductile rocks, ceramics; homogeneous single crystal and organic glass) were damaged by falling weight, and the highly resolved FL time series were recorded. The FL amplitude distributions in the time series were constructed in order to establish a prevailing statistical law that governs the energy release in primary damage events occurring in different materials.

SAMPLES AND EQUIPMENT

Tested brittle solids were granite, silica ceramics, and silicon carbide; marble and poly (methylmethacrylate) (PMMA) represented ductile materials. The samples were shaped to blocks of approximately 20×20×30 mm with polished faces.
A schematic diagram of the experimental setup is depicted in Fig. 1a. The samples were placed on a massive metal support covered with a grease layer in order to reduce parasitic vibrations. A surface damage was produced by the pointed striker positioned on the upper face of the sample, on which a 100 g weight dropped. The data acquisition system was triggered in the moment of contact between the weight and the striker. Photographs of damaged samples are shown in Fig. 1 (cut-off).

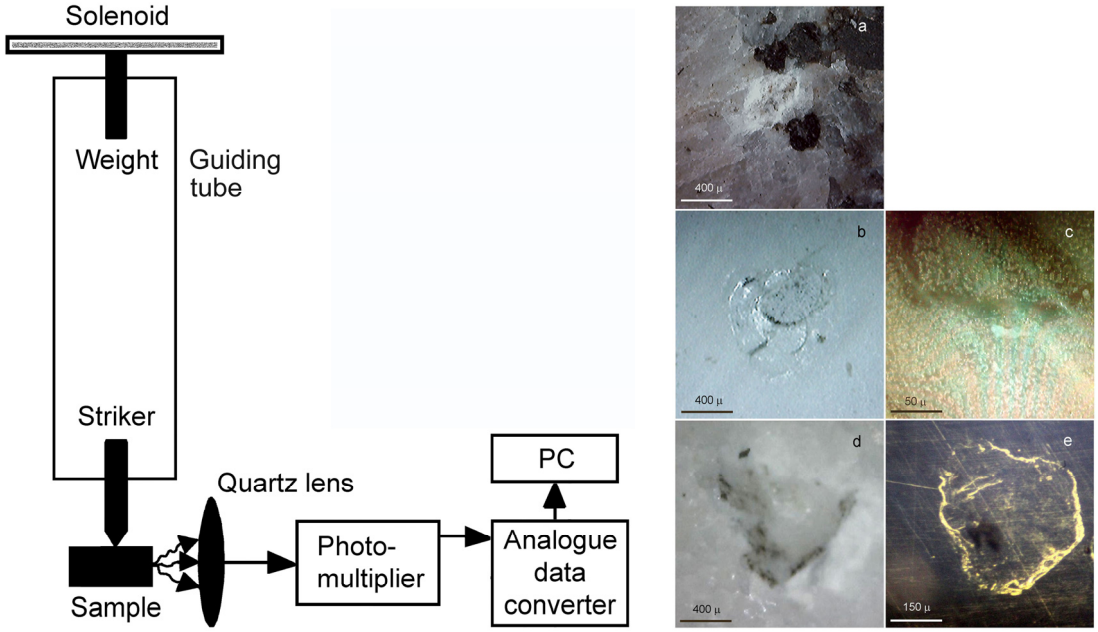

Figure 1: Schematic diagram of the experimental setup and photographs of impact-induced damages in granite (a), silica ceramics (b), silicon carbide (c), marble (d), and organic glass (e).

The FL radiation was collected from the side face of the sample by a quartz lens and directed onto a photomultiplier FEU136. Thus, only the light excited by bond breakage at the lateral surface of the sample, which was optically isolated from the damaged surface, was detected.
An analogue-to-digital converter ASK-3106 provided the dynamic range 2 mV to 10 V (70 dB) in the time range 10 ns to 100 c. The converted (digital) FL signals were directed to and stored in a PC. The duration of all recorded time series was 1.3 ms.

TIME SERIES

Fig. 2 shows the AE time series from impact fractured samples. A delay of about 70-90 μs between the instance of weight-striker contact and the series beginning was determined by the traveling time of the elastic wave through the

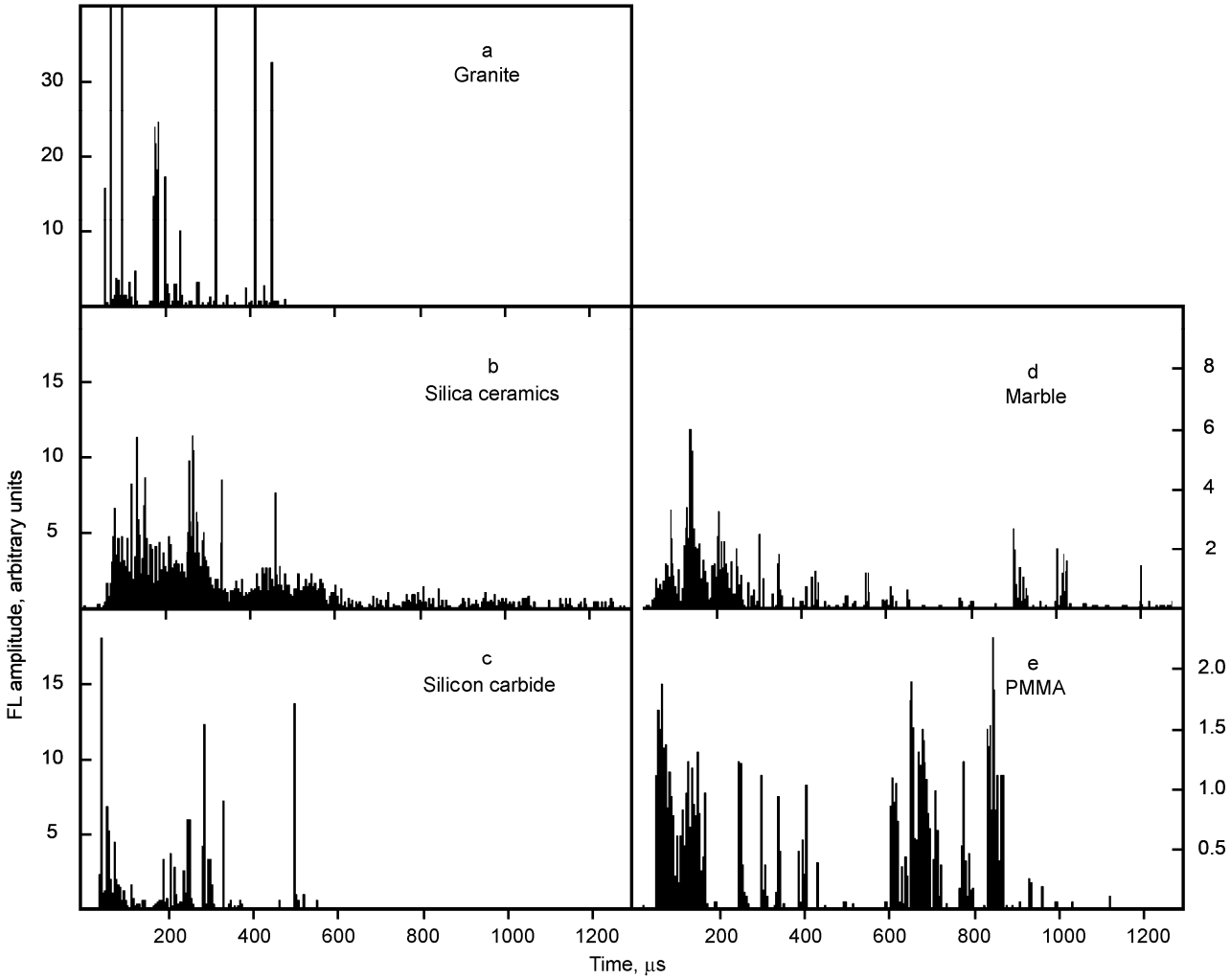

Figure 2: Time series of FL signals from fracturing samples.

striker. The impact produced a localized "macroscopic" damage on the sample surface, and generated microscopic failures throughout the sample including lateral faces, from which the emitted light was collected. The signal intensity depended both on the sample hardness (which influences the damage size), and on the quantum yield of luminescence. The FL amplitude is proportional to the energy release in damage events. Therefore, the amplitude time series were used for constructing the energy distributions in the form of dependence $\log_{10}N(E>E')$ versus $\log_{10}E'$, where $N(E>E')$ is the number of events characterized with the energy E exceeding a threshold value E'. Each energy distribution was plotted both in double- and semi-logarithmic coordinates (Fig. 3a and 3b, respectively). One can see that the distributions belonging to brittle materials contain log-linear portions (Fig. 3a), which represent the dependence:

$$\log_{10}N(E>E') \propto -b\log_{10}E' \quad (1)$$

(here b is the constant). Eq. (1) can be rewritten in the form of the power law:

$$N(E>E') \propto E'^{-b}. \quad (1a)$$

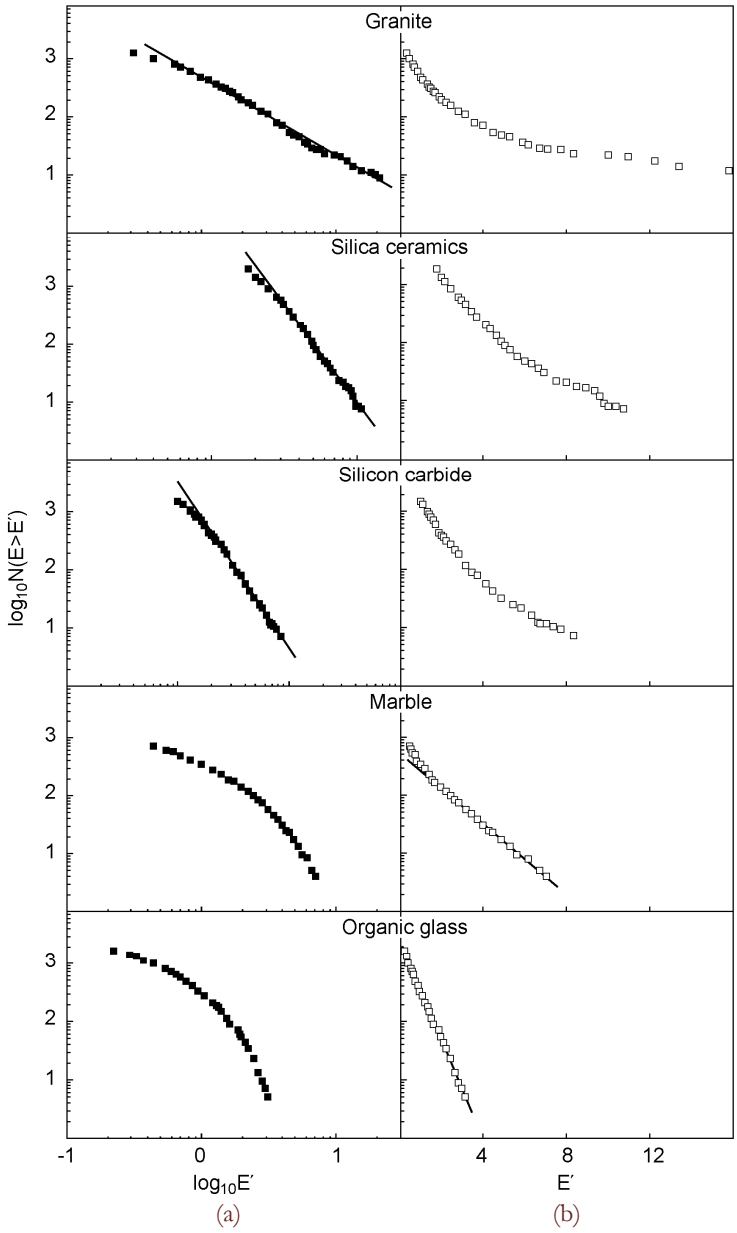

Figure 3: The same experimental dependences $N(E>E')$ versus E' plotted in double-logarithmic (a) and semi-logarithmic (b) coordinates; straight lines in (a) and (b) fit Eq. (1) and Eq. (2), respectively.

In ductile marble and PMMA, the $\log_{10}N(E>E')$ versus $\log_{10}E'$ graphs do not exhibit log-linear dependences but being replotted in semi-logarithmic coordinates (with linear scale along the energy axis, Fig. 3b) these ones become well approximated with straight lines according to the relation:

$$\log_{10}N(E>E') \propto -aE' \tag{2}$$

where a is the constant. Relation (2) is equivalent to the exponential law

$$N(E>E') \propto \exp(-aE') \tag{2a}$$

which is specific for random events occurrence. Correspondingly, neither brittle materials exhibit the exponential dependence (2), nor the energy distributions in ductile materials follow the power law (1). (We remind that the consideration concerns primary damage events detected at the nanostructural scale level.)

DISCUSSION

The statistical analysis of the time series showed that the energy distributions of FL pulses in both heterogeneous and homogeneous brittle materials follow the power law indicative of long-range interactions between primary damage events. Random (exponential) energy distributions were found in experiments with marble and organic glass that is in materials with pronounced plasticity. The absence of the correlated damage accumulation in this case was quite surprising because these materials exhibited the FL series evidencing multiple (statistically significant) bond breakage. However, this result points out a necessity to introduce some corrections in common interpretations of the role of structural heterogeneities, which were developed for explaining some cooperative phenomena in fracture.

The cooperative effects result from the interactions between multiple individual failures, which are realized through propagating elastic waves excited by local structural perturbations [9, 10]. High plastic deformation prior to the bond rupture suppresses the elastic excitations thus disturbing dynamic cross-coupling between nucleating defects. As a result, the damage accumulation in ductile materials proceeds in an extensive manner that is the appearance of a defect does not affect efficiently the nucleation of other ones.

This means that the prevalence of either correlated or random damage initiation at the scale level of basic structural heterogeneity (at the nanostructural level) depends on the degree of microplasticity in the given material, which determines the efficiency of long-range elastic interactions

CONCLUSION

Fractoluminescence is the effective method for monitoring the nucleation of defects in deformed/fractured dielectrics at the level of basic structural links. The FL sensitivity depends on the damage size and quantum yield of luminescence. In this work, the FL technique was applied for studying the primary damage accumulation in a set of solids differing in their mechanical properties. The statistical analysis of the FL time series emitted from impact damaged solids revealed the power law energy release distributions (scaling) in brittle materials, and exponential (Poisson-like) distributions in ductile materials. At the same time, the microscopic heterogeneity of materials did not determine the prevailing (correlated or random) energy pattern at the nanostructural scale level.

REFERENCES

[1] Bowman, D.D., Ouillon, G., Sammis, C.G., Sornette, A., Sornette, D. An observational test of the critical earthquake concept, J. Geophys. Res., 103 (1998) 24359-24372.

[2] Carpinteri, A., Puzzi, S., Complexity: a new paradigm for future mechanics, Frattura Integrità Strutturale, 10 (2009) 3-11.

[3] Mamalimov, R.I., Sinani,A.B., Chmel, A.E., Shcherbakov, I.P., Initiation of impact fracture in SiO_2 ceramics, Tech. Phys., 58 (2013) 1453-1458.

[4] Momon, S., Moevus, M., Godin, N., R'Mili, M., Reynaud, P., Fantozzi, G., Fayolle, G., Acoustic emission and lifetime prediction during static fatigue tests on ceramic-matrix-composite at high temperature under air, Composites Part A: Appl. Sci. Manufacturing, 41 (2010) 913-918.

[5] Amitrano, D., Rupture by damage accumulation in rocks, Intern. J. Fract., 139 (2003) 369-381.

[6] Davydova, M., Uvarov, S., Fractal statistics of brittle fragmentation, Frattura ed Integrità Strutturale, 24 (2013) 60-68.

[7] Chandra, B.P., Mechanoluminescence in luminescent solids, in D.R. Vij (Ed.), Luminescence of solids, Plenum Press, New York, (1998) 301-345.

[8] Kawaguchi, Y., Time-resolved fractoluminescence spectra of silica glass in a vacuum and nitrogen atmosphere, Phys. Rev. B, 52 (1995) 9224-9228.

[9] Kuksenko, V., Tomilin, N., Chmel, A., The rock fracture experiment with a drive control: A spatial aspect, Tectonophysics, 431 (2007) 123-129.

[10] Telesca, L., Lovallo, M., Investigating non-uniform scaling behavior in temporal fluctuations of seismicity, Nat. Hazards Earth System Sci., 8 (2008) 973-976.