Scaling in the Mechanoluminescence of Shocked Quarz Rods

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Abstract. The dynamic fragmentation was studied in the impact experiments with fused quartz cylindrical rods using a gas gun [1]. Impact leads to the formation of fracture surfaces, which produce an intensive light emission (mechanoluminescence or fractoluminescence). Mechanoluminescence was registered by two PMT connected with the oscilloscope. Mechanoluminescence was in form of impulses with typical rise time 2-5 ns and fall time 5-50ns. It was found that the impulse rate was not decreases monotonically but there was some kind of bursts or avalanches and fragmentation process time is 2-4 orders longer than acoustic time. We found that distribution of intervals between luminescence impulses is a power law distribution. Therefore, we can conclude that time interval distribution show evidence of scaling, which suggests the possibility of self-organized criticality in fragmentation.

Introduction

Per Bak et al. in their paper "Self-Organized Criticality: An Explanation of 1/f Noise" mentioned: "The common feature for these systems is that the power-law temporal or spatial correlations extend over several decades where naively one might suspect that the physics would vary dramatically. Dynamical systems with extended spatial degrees of freedom naturally evolve into self-organized critical structures of states which are barely stable. We suggest that this self-organized criticality is the common underlying mechanism behind the phenomena described above. The combination of dynamical minimal stability and spatial scaling leads to a power law for temporal fluctuations. The noise propagates through the scaling clusters by means of a "domino" effect upsetting the minimally stable states. Long-wavelength perturbations cause a cascade of energy dissipation on all length scales" [2]. To confirm the fact that the fragmentation exhibits SOC, we need to establish the existence of a power law for temporal and spatial quantities. The evidence of the spatial scaling for the fragmentation of brittle materials under different loading conditions was given in paper [1] . For measurement of temporal scale we developed an experimental device to determine the time interval between the impulses of the light reflected from the newly created fracture surfaces. In our investigation (fragmentation of quartz rods under dynamic loading), SOC means that there exist:

- power law distribution of fragment size;
- power law distribution of time interval between the impulses of the light reflected from newly created surfaces.

Experiment

The fragmentation statistics was studied in recovery dynamic experiments with fused quartz cylindrical rods which have 10 mm diameter and 120 mm length.

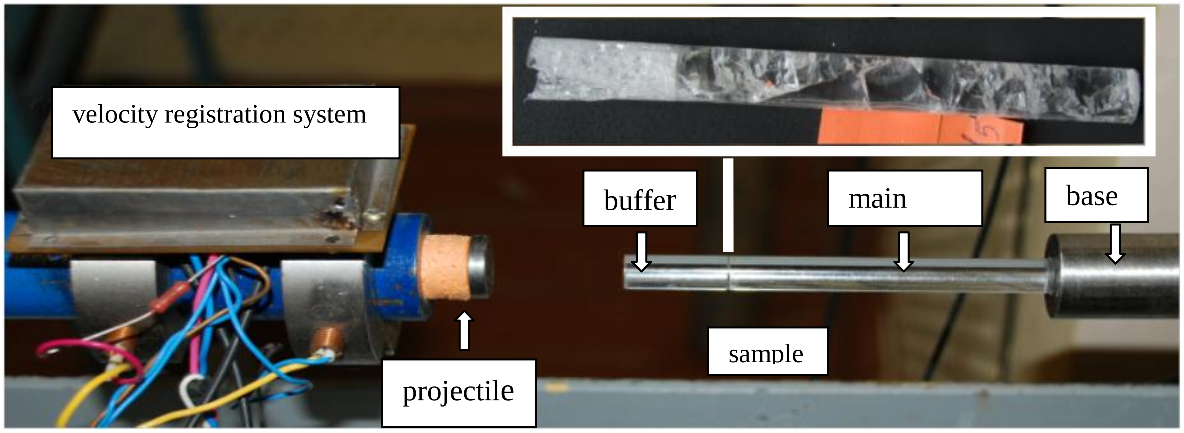


Figure 1. Ballistic set-up. An example of the fragmentation pattern is given in the upper right-hand corner.

Rods were loaded by ballistic set-up, which consisted of a gas gun with bore diameter of 19.3 mm, a velocity registration system and a base where the specimen was placed (Fig. 1). The sectional rod was composed of a buffer and the main part covered by an elastic shell. The buffer was used for realization of uniaxial loading produced by a cylindrical projectile of mass 13.9 g accelerated up to the velocities of 6-50 m/s.

In order to check influence of loading conditions on fragmentation statistics two types of boundary conditions at the rear end were checked. Rear end of the sample was glued to the steel rod and rear end was free [1]. We found that statistics of fragment distribution does not change significantly so next experiments were carried out with a free rear end of the sample. The mass of the fragments corresponding to the maximum of the probability density function is independent of the projectile energy. To obtain the fragment size distribution, the technique described in the previous experiments [1] was used, which made it possible to get the distribution obeying the scaling law. This experiments are presented in the talk “*Fractal Lows for Spatial and Temporal Variables of Brittle Fragmentation*” by Davydova M. and Uvarov S. at ECF12. The scheme given in Figure 2 illustrates the experimental technique used to measure the distribution of time quantities.

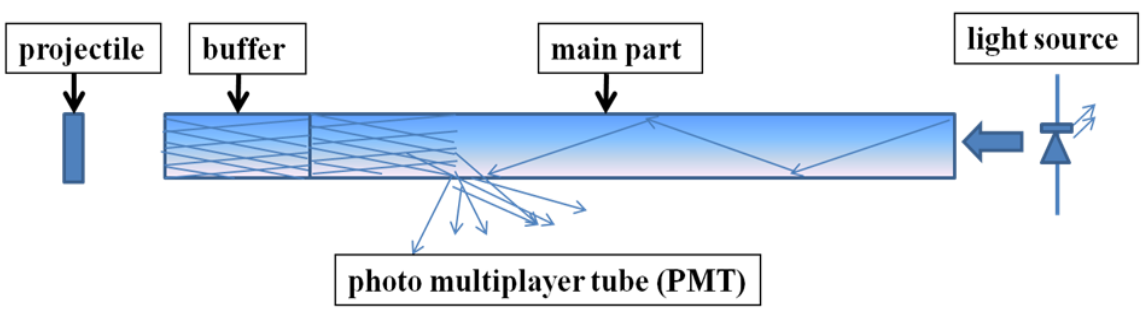


Figure 2. Scheme of the experiment for measuring temporal statistics of fragmentation. Light source was used for visualizing the cracks in the sample.

It is known [3] that cracking of quartz leads to emission of light known as fractoluminescense of mechanoluminescence. The light intensity was registered by the Photo Multiplayer Tube connected with the oscilloscope (oscilloscope sample rate is 1 GHz). The appearance of the new surfaces produces the impulses with a sharp front with typical rise time about 5 ns (Fig. 3).

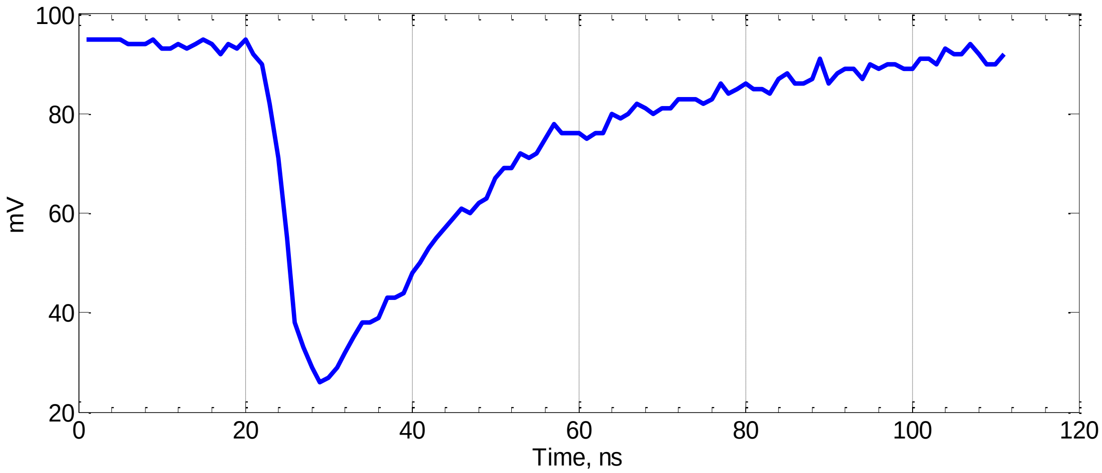


Figure 3. Typical fractoluminescence event.

Figure 4 shows the signal from the oscilloscope. One can note that fragmentation process lasts 2-3 decades longer than loading time (20 μs). Pulse rate does not decrease monotonically, instead of this one can note avalanches or bursts of pulses similar to the avalanches on the sand pile which is common illustration of SOC.

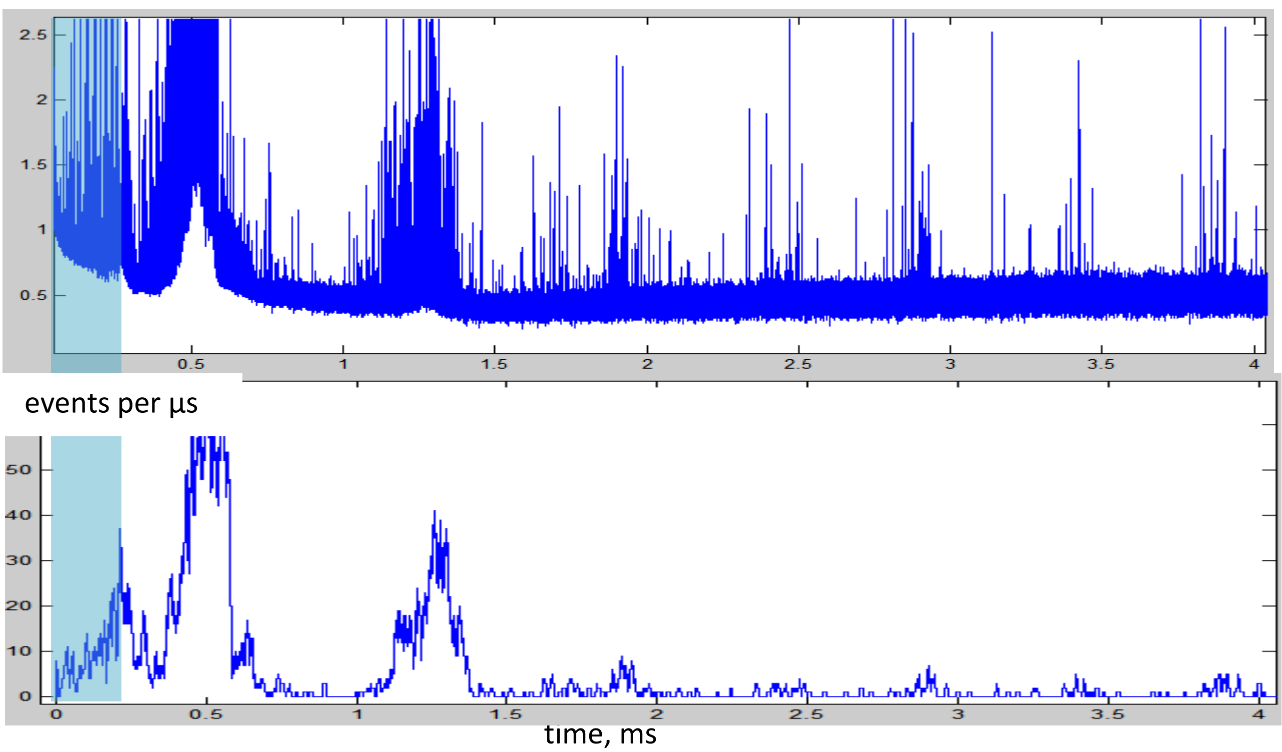


Figure 4. Signal from the oscilloscope (upper, polarity of pulses is reversed) and pulse rate (lower). Time scale is the same for both graphs.

Data processing

The first step of data processing is signal filtration. Because fractoluminescence pulses have a very short rise time application of the high-pass filter to the original signal increase signal-to-noise ratio and makes possible to measure time intervals between events. The definition of the size of time interval between the impulses shown at the Figure 5. The second step involves measuring the distance between the green bars showing a sharp rise in impulse. We consider only the impulses which are above some discrimination level (the red line). Discrimination level determined by noise level in the way that not more than 1 false positive pulse was detected on the reference signal. Reference signal was taken before loading.

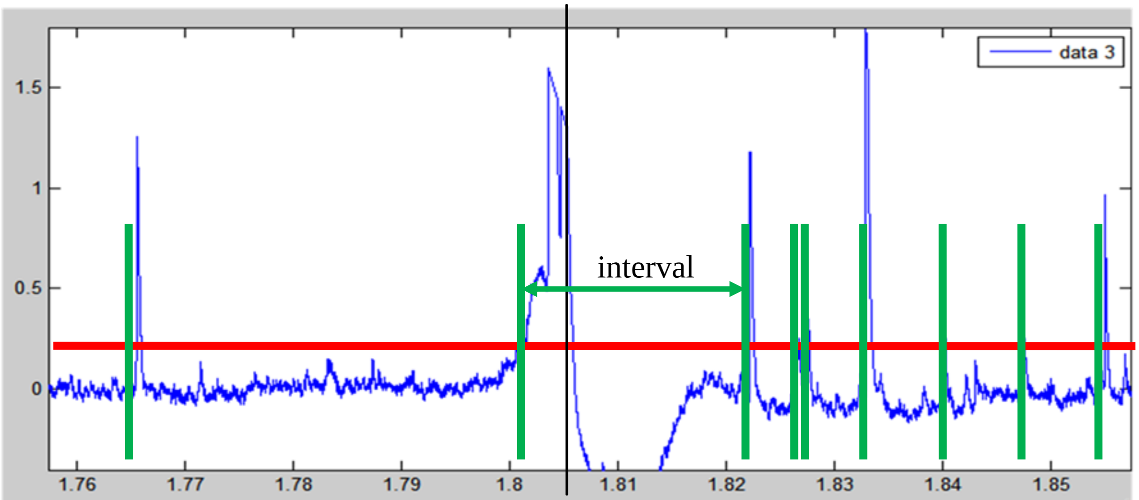


Figure 5. Determination of the size of time interval between the impulses of the light reflected from the facture surfaces.

The cumulative distribution function of the time interval in the double logarithmic plot (Figure 6) is fitted by the straight line (total number of points 1073).

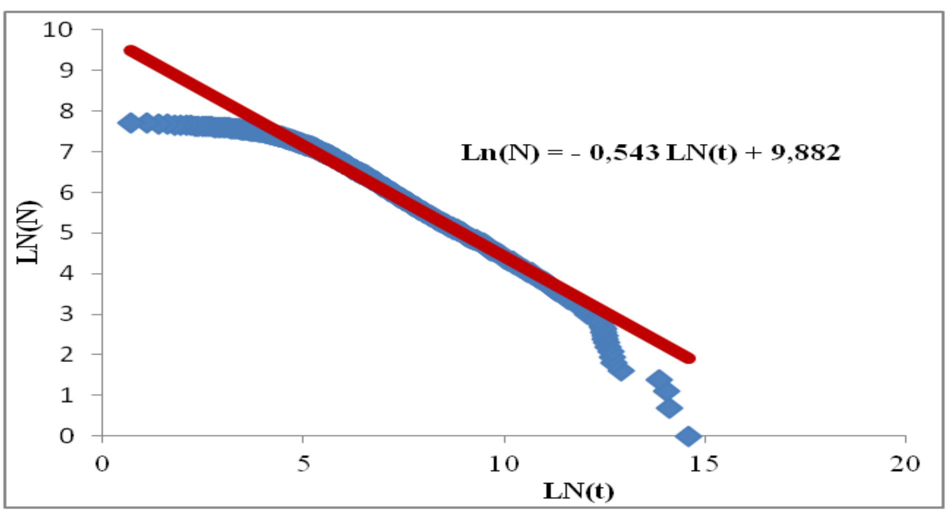
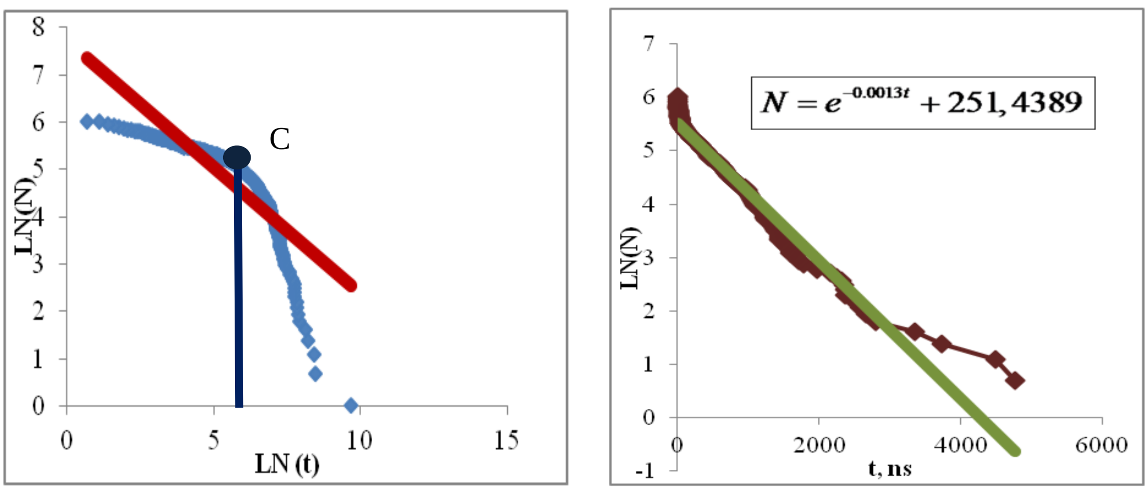


Figure 6. Cumulative distribution function of time interval in the double logarithmic plot.

At small sizes (77 points – 7.1761 % of the total number of points), the curve deviates from the straight line because the size of time interval is comparable with the oscilloscope sample rate (1 GHz). The falloff at the largest interval sizes (16 points – 1. 5% of the total number of points) is due to finite-size effects. In this case the time interval is comparable with the process time. The central part is the line covering 91.3% of the total number of points. The process of light reflection looks like the process of avalanche spreading (Fig. 4). The lower plot represents the event frequency. The events are distributed in blocks. We have analyzed the time interval distribution in avalanches and found that the distribution at the initial stage (marked in blue in Fig. 4) cannot be described by the power law.

The left plot in Figure 7 illustrates the distribution at the initial stage in double logarithmic coordinates. In the right plot in Figure 7, only the vertical coordinate is logarithmic. The time interval distribution is subjected to the exponential law.



a) b)

Figure 7. a) Cumulative distribution function of time interval for initial stage in a double logarithmic plot. b) Cumulative distribution function of time interval for initial stage in a coordinate system Ln (N) –time t.

An exponential functional form requires a characteristic length scale which can be defined as

$$X_{ch} = tV \, , \tag{1}$$

where *Xch=2.6 mm* is the characteristic size, *t* is the x-coordinate of point C (t= 457 ns), and *V=5800 m/s* is the sound velocity in quartz. We suppose that this length scale correlates with the impactor thickness The initial stage statistics does not change the total statistics, because only 10% of the points belong to the initial stage.

Investigation of the fragments by optical microscopy (Fig. 8.) reveals that surface of the fragments is not smooth so there is no simple relationship between pulse amplitude and crack size as in [3] where cracks are represented as smooth disk-shaped objects.

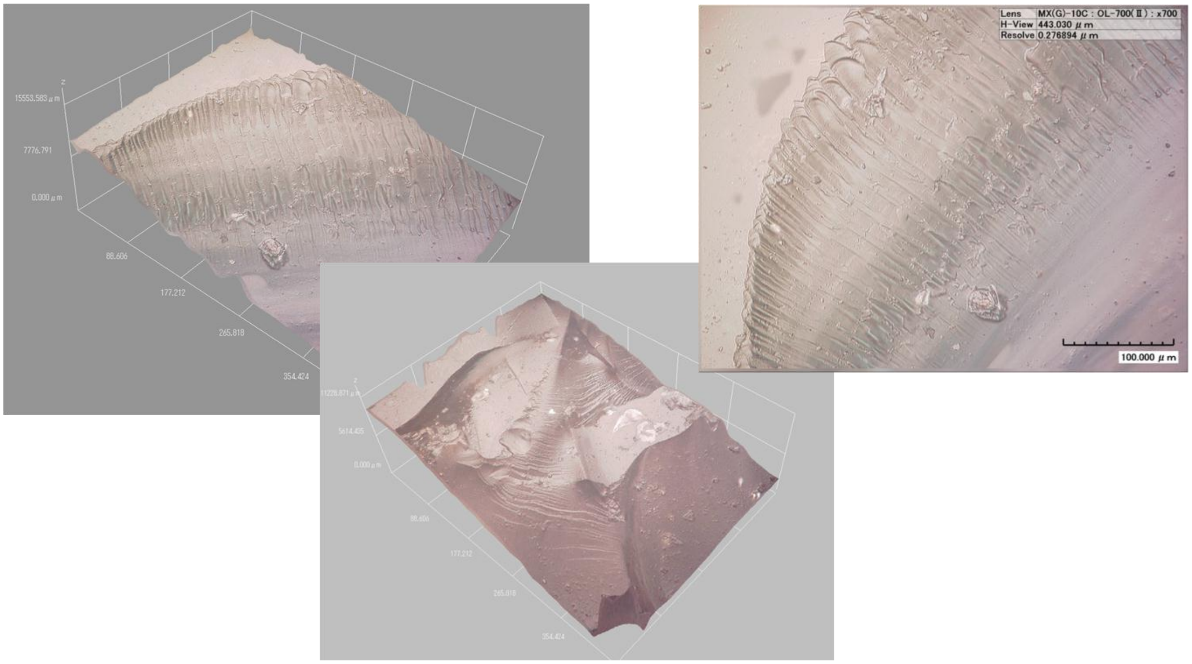


Figure 8. Fracture surface of quartz. Optical microscopy.

Summary

In our experiments we found that exist:

- power law distribution of fragment size;
- power law distribution of time interval between the impulses of the light reflected from newly created surfaces.

So we can suppose that self-organized criticality is the underlying mechanism of fragmentation except initial stage where exponential distribution is observed.

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