Monitoring the failure mechanisms in metal matrix syntactic foams during compression by acoustic emission

Csilla Kádár[1,*], Kristián Máthis [2], Imre N. Orbulov[3,4], František Chmelík[2]

[1]Department of Materials Physics, Loránd Eötvös University, Pázmány P. stny. 1/A, H-1117 Budapest, Hungary

[2]Department of Physics of Materials, Charles University, Ke Karlovu 5, CZ12116 Prague 2, Czech Republic

[3]Department of Materials Science and Engineering, Budapest University of Technology and Economics, Műegyetem rkp. 3. H-1111, Budapest, Hungary

[4]MTA–BME Research Group for Composite Science and Technology, H-1117 Budapest, Hungary

Abstract

Syntactic foam containing hollow ceramic spheres with an average outer diameter of 1.45 mm and wall thickness of 58 μm was produced using the pressure infiltration technique. This paper presents the analysis of the compressive deformation mechanisms of these syntactic foams using the acoustic emission (AE) technique. The active

[*] Corresponding author. E-mail addresses: kadar@metal.elte.hu (Cs. Kádár), mathis@met.mff.cuni.cz (K. Máthis), orbulov@eik.bme.hu (I. N. Orbulov), chmelik@met.mff.cuni.cz (F. Chmelík)

deformation mechanisms are determined by sequential k-means analysis of the AE data. The analysis revealed three dominant deformation mechanisms: plastic deformation of the cell walls, sphere fracture, and cell wall collapse. The AE results obtained are in good correlation with the findings of the visual inspection of the surface of the specimen, suggesting that the active deformation mechanisms in the whole volume of the specimen can be determined by this technique.

Keywords

Porous materials; Mechanical properties; Acoustic emission

Introduction

Metal matrix syntactic foams (MMS foams) belong to a relatively new class of materials with outstanding mechanical and physical properties [1-3]. MMS foams comprise a metal matrix containing ceramic hollow spheres. Because the strong and stiff ceramic shells delay the collapse of the cells, MMS foams exhibit higher strength than conventional metal foams. Due to this unique combination of properties, MMS foams are suitable for structural applications as well as for energy absorption systems in the transportation industry.

In applications such as energy absorbers, studying the damage evolution and related failure mechanisms are important. The deformation and damage mechanisms have been investigated by various experimental methods, including digital macro-imaging [4], infrared (IR) thermography [3], X-ray tomography [2], and neutron diffraction [1]. In these papers, the load transfer from the matrix to the hollow spheres and the influence of the matrix composition on strain localization were examined. The deformation band formation and onset stress of the matrix failure were also discussed in detail. However, the imaging methods are limited to the observation of the specimen surface and therefore do not provide information about the bulk. The X-ray tomography and diffraction methods are suitable to characterize the internal features of the materials, but these methods are time consuming and are only quasi in-situ – the deformation must be stopped during recording.

Acoustic emission (AE) tests combine high time resolution (μs range) and the ability to characterize the entire volume of the specimen. AE is defined as transient elastic waves generated within the material due to sudden localized structure changes, such as collective dislocation motion or crack initiation and propagation. Thus, AE yields information on the dynamic processes involved during the deformation of the material. In the present work, MMS foams consisting of a commercially pure (cp) aluminum matrix and ceramic spheres were deformed in compression at room temperature. We simultaneously performed an AE measurement and a video recording of the surface to reveal the active deformation mechanisms. Next, we applied the recently developed sequential k-means method (ASK) [5] on the AE data to separate the particular AE events originating from different source mechanisms.

Experimental

The materials investigated were produced using the pressure infiltration technique. The detailed manufacture process can be found in [6]. For the investigation, technical purity Al 99.5 (99.5 wt% Al, 0.2 wt% Si, 0.3 wt% Fe) matrix containing 65 vol% hollow spheres was selected. The hollow ceramic spheres (consisting of 35 wt% Al_2O_3, 45 wt% SiO_2 and 20 wt% mullite) were produced by Hollomet GmbH. The average outer diameter and wall thickness of the spheres were 1.45 mm and 58 μm, respectively.The density of the MMC foam was 1.81 g·cm^{-3}.

An Instron® 5882 machine was used for compressive testing. Four specimens, 30 mm in length and 14 × 14 mm^2 in cross-section, were deformed with a constant cross-head speed of 0.03 mm·s^{-1} at room temperature. The deformation of the surface was recorded by a high-resolution digital camera.

The AE signals were recorded simultaneously with the deformation test data using a computer controlled PCI-2 device (Physical Acoustic Corporation - PAC) in waveform streaming mode, i.e., no threshold level was applied during the AE recording. A PAC Micro-sensor was mounted on the specimen using a clothespin and silicon grease. The AE testing set-up consisted of the Micro30S sensor (10 mm in diameter) attached to a 2/4/6-type preamplifier (both manufactured by (PAC)) giving a gain of 40 dB. The amplified AE signal was recorded by a Micro-II acquisition board from PAC, build into a PC. The circuit diagram of the set-up is given in Ref. [7].

Results and discussion

The deformation curve is plotted in Fig. 1a. (dashed line). The stress- strain curve has a characteristic shape, i.e., after the quasi-linear region, the curve reaches a peak stress. Subsequently, a stress drop occurs, which is followed by an extended plateau. The AE signal reaches its maximum in the region around the peak stress (Fig. 1a., blue line).

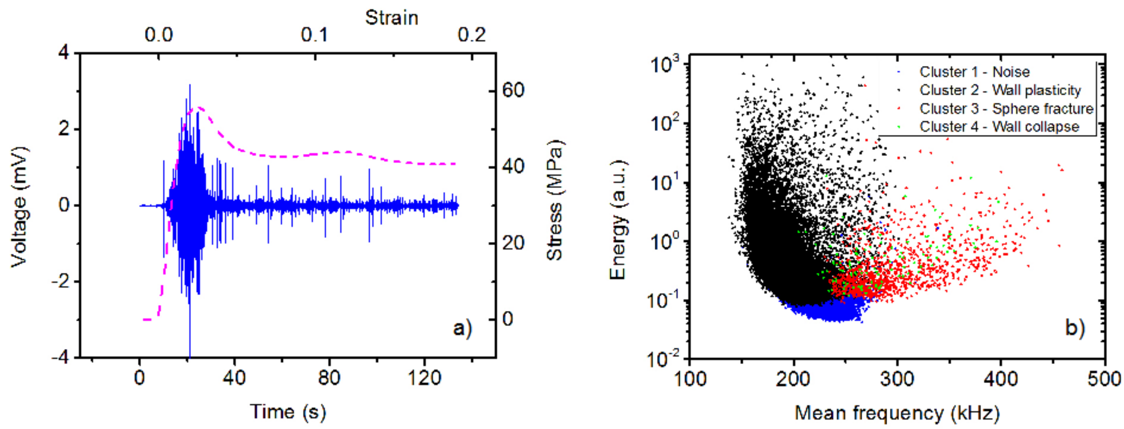

Fig. 1. AE signals (a) as measured (blue line) compared to the stress-strain curve (dashed line) (b) after using ASK procedure showing the 2D projection to the energy - mean frequency space of the clusters.

To identify the particular deformation mechanisms during straining, the AE signals were analyzed using the ASK procedure. ASK analysis, introduced recently by Pomponi and Vinogradov [5], uses a statistical approach for classifying the AE signals with different emitting sources. Because the details are available in [5], only a brief overview of the main steps used in the current work is given here.

- The recorded AE signals are sectioned using so-called "*time windows*". The window size can be varied; in the present work, 2 *ms* was used.
- For each time window, the power spectral density (PSD) of the signal is calculated.
- The characteristic features (like median frequency, peak value, energy, kurtosis, etc.) of the PSD are determined.
- The first cluster is defined by the parameters of the PSD in the first window.

- PSDs in the consecutive windows are analyzed one by one. If the statistical properties of a given PSD are similar to those in an already existing cluster, then this PSD is assigned to this cluster. Otherwise a new cluster is established. The conditions for forming a new cluster are based on the k-means method.

When the clustering procedure is completed, a dominant AE source mechanism is assigned to each cluster. This assignment consists of three basic steps:

1. Checking at which strain or stress the number of elements in a given cluster starts to increase. For example, the elements in first cluster must belong to the background noise because recording the AE data starts *before* the deformation starts.
2. Checking the characteristic features of the PSDs, for example, energy, frequency distribution, and so on. Typically, noise and dislocation motion emit a low frequency signal [5].
3. Comparison of the time evolution of the number of elements in a given cluster with the supplementary dataset. In our case, the digital camera recording was compared to the ASK data.

The ASK analysis identified four clusters (Fig.1b.). The number of the elements in the different clusters as a function of time is shown in Fig. 2. The following dominant source mechanisms can be assigned to the different clusters.

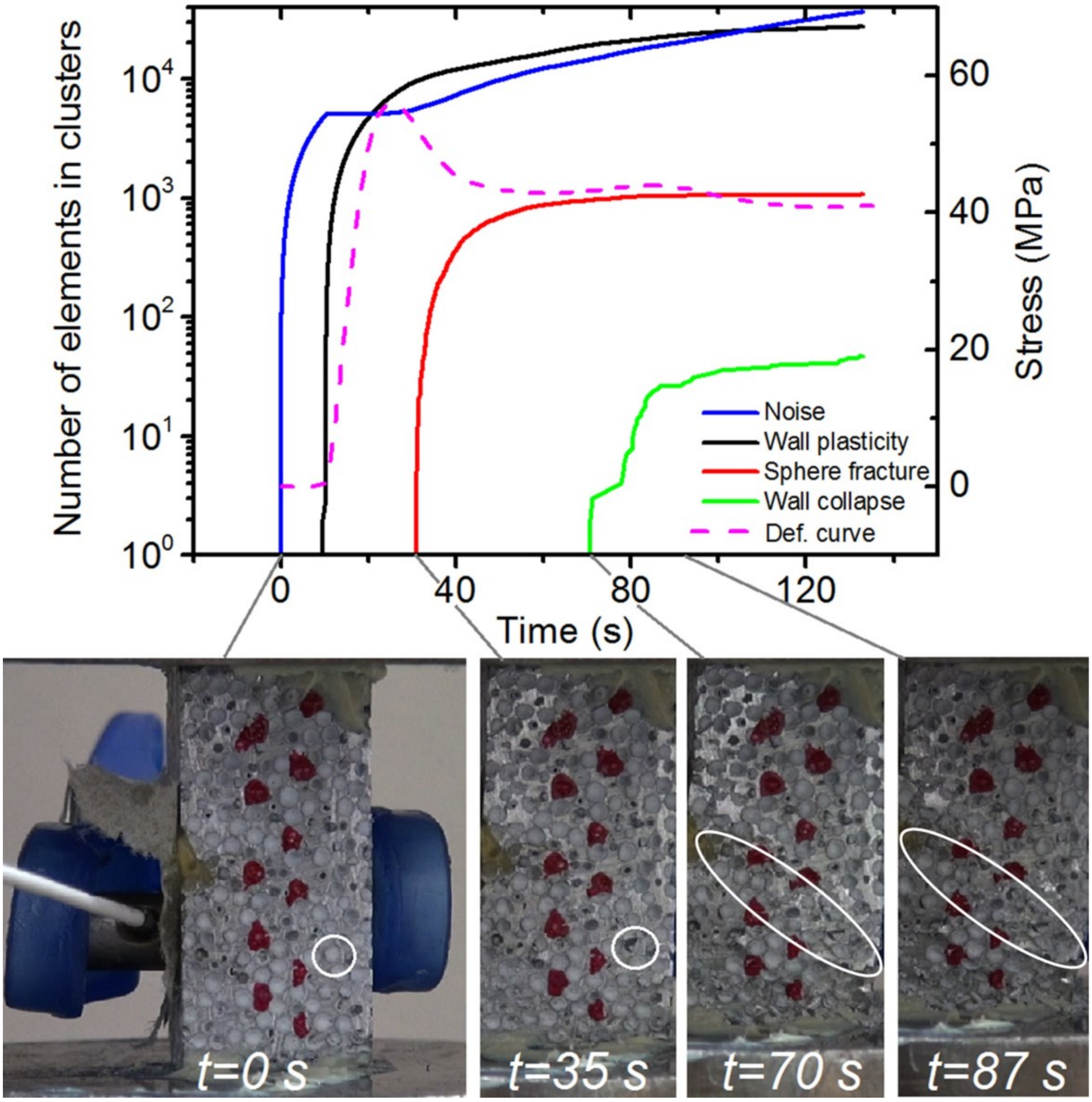

Fig. 2. Time evolution of the cumulative number of elements in the AE clusters assigned to the noise (blue line); plastic deformation of walls (black line); sphere fracture (red line); and wall collapse (green line). The deformation curve is displayed by the magenta dashed line. Subfigures on the bottom show the deformation of the surface of the MMC foam when a cluster appears.

Cluster 1: *Noise* (color code in figures: blue)

This cluster appears first, before launching the deformation test, indicating a contribution of the background noise to this cluster because the unstressed sample does not emit AE. In addition to the rapid rise of the number of elements in Cluster 1 at the beginning of the AE measurement, the number of elements in this cluster also considerably increases from approx. 30 *s*. In this case, AE originates from the friction between the (broken) ceramic spheres and the matrix material. The AE signals in this cluster have low energy (E< 0.1 a.u. – cf. Fig. 1b.) and have a continuous character (Fig. 3a.). Both of these features have been reported as characteristic of the noise signal [8].

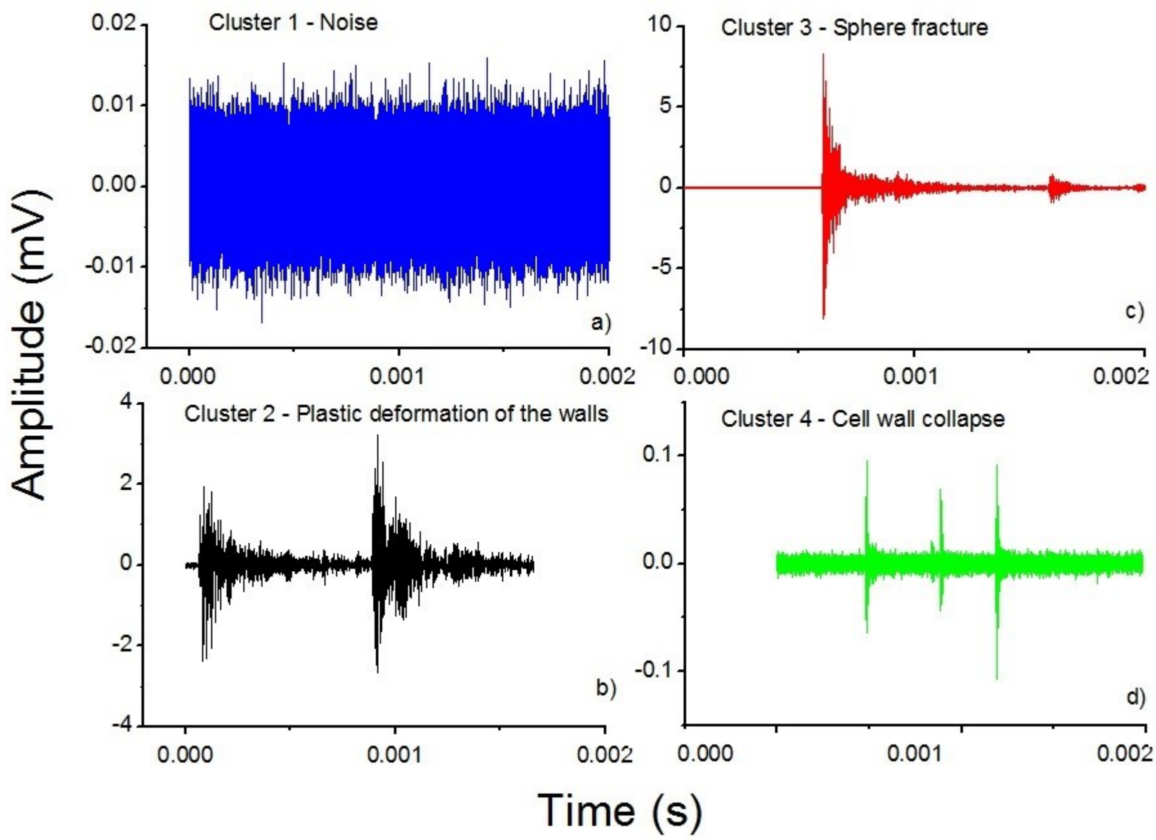

Fig. 3. Characteristic waveforms in the particular clusters: a) Cluster 1 – noise; b) Cluster 2 – plastic deformation of metallic walls; c) Cluster 3 – sphere fracture; d) Cluster 4 – wall collapse.

Cluster 2: *Plastic deformation of the metallic walls* (color code in figures: black)
The number of events in this cluster starts to increase at the beginning of the deformation, i.e., at a low applied stresses. This behavior is characteristic for plastic deformation of metallic walls of foam, which is mainly governed by dislocation motion. The dislocation-type AE events usually consist of an array of burst signals (cf. Fig. 3b.) [9]. The large energy signals are probably emitted by densely populated dislocation avalanches at the beginning of straining. As the deformation proceeds, the energy of the events in this cluster decreases and the frequency range increases as a consequence of the decreasing mean free path of the dislocation movement.

Cluster 3: *Sphere fracture* (color code in figures: red)
This cluster appears after reaching peak stress. The wide energy and frequency spectra indicate that AE signals originating from the fracture of ceramic spheres contributed to this cluster. The typical burst character of the AE signals (Fig. 3c.), which have virtually zero risetime (i.e., the peak value of the signal is reached immediately), supports this assumption.

Cluster 4: *Cell wall collapse* (color code in figures: green)
This cluster becomes significant at a later stage of deformation (> 70 s). The typical signals in this cluster exhibit a sequence of small bursts, each of which has a negligible

rise time (Fig. 3d.). The energy and frequency distributions of the signals are wide, which can be substantiated by the fact that, within a time period, many walls with different characteristics (e.g., thickness and length) are involved in the process (practically, the walls in the deformation zone).

According to the ASK analysis, the main deformation mechanism is the plastic deformation of the metallic walls, occurring almost from the beginning of the compression until approx. $\varepsilon=0.04$ (which corresponds to 31 s in case of the first sample). The AE signal waveforms connected with these mechanisms are similar to those observed for deformed unreinforced foams [10]. In addition, as was found in [10], plastic deformation occurs due to strain localization, even at low stress. Other researchers also found that in the case of a lower-strength and ductile matrix with ceramic spheres, the MMS foams deform by matrix plasticity before sphere fracture occurs [2]. After reaching peak stress, the stresses acting on the spheres are high enough to induce fracture, as observed both on the video recording (see in Ref. [11]) and through the AE response. The first ceramic crumble that can be seen on the video appears at the same time as Cluster 3 (Fig. 2 subfigure, t=30 s, circled area). Fig. 2 shows that as the number of elements in Cluster 3 increases, the number of elements in both Cluster 1 and Cluster 2 increase. As previously mentioned, the increase in the number of elements in Cluster 1 can be attributed to the friction between the broken ceramic spheres and the matrix material. The increase in the number of elements in Cluster 2 is probably because the deformation is not localized in a small volume, i.e., it can also take place in regions with yet intact spheres, as shown in the supplementary video file in [11]. At approximately 70 s (~ 9% of applied strain), a small increase in the stress can be observed on the deformation curve. The video recording clearly shows that a deformation band appears at this moment (Fig. 2 subfigure, t=70 s, circled area). AE is sensitive to this change because Cluster 4 is formed exactly at this moment, characterizing the collapse of the cells within this band ([11]). A similar connection was found between the video and the AE data for each sample.

Conclusions

The AE response during the compression test of a metal matrix syntactic foam was recorded in this work. The ASK analysis of AE data revealed the following dynamics of the deformation mechanisms:

- At the initial stage, the governing mechanism is the plastic deformation of cell walls.
- The sphere fracture begins soon after reaching peak stress.
- In the plateau stress region, the AE signal originated from the collapse of cell walls in deformation bands becomes significant.

The AE results obtained are in good correlation with the findings of the visual inspection of the surface of the specimen.

Acknowledgement

The authors are grateful for the financial support of the Czech Science Foundation under the contract 15-10821S. This paper was supported by the János Bolyai Research Scholarship of the Hungarian Academy of Sciences (I. N. Orbulov).

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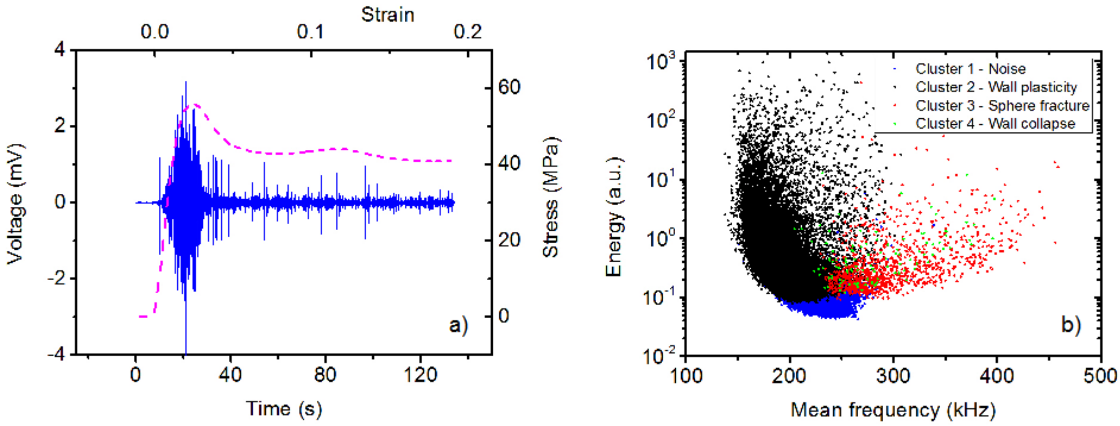

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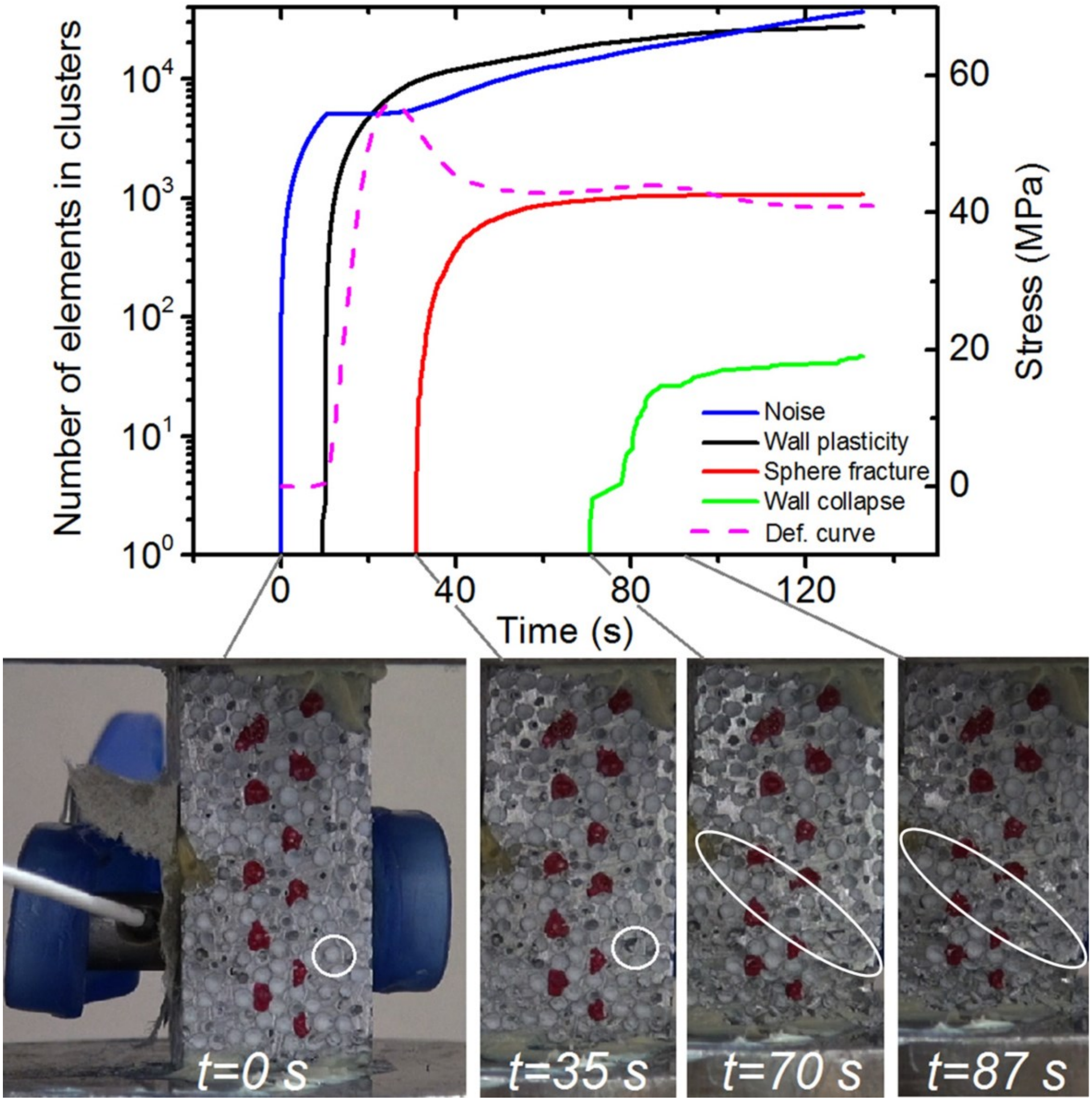

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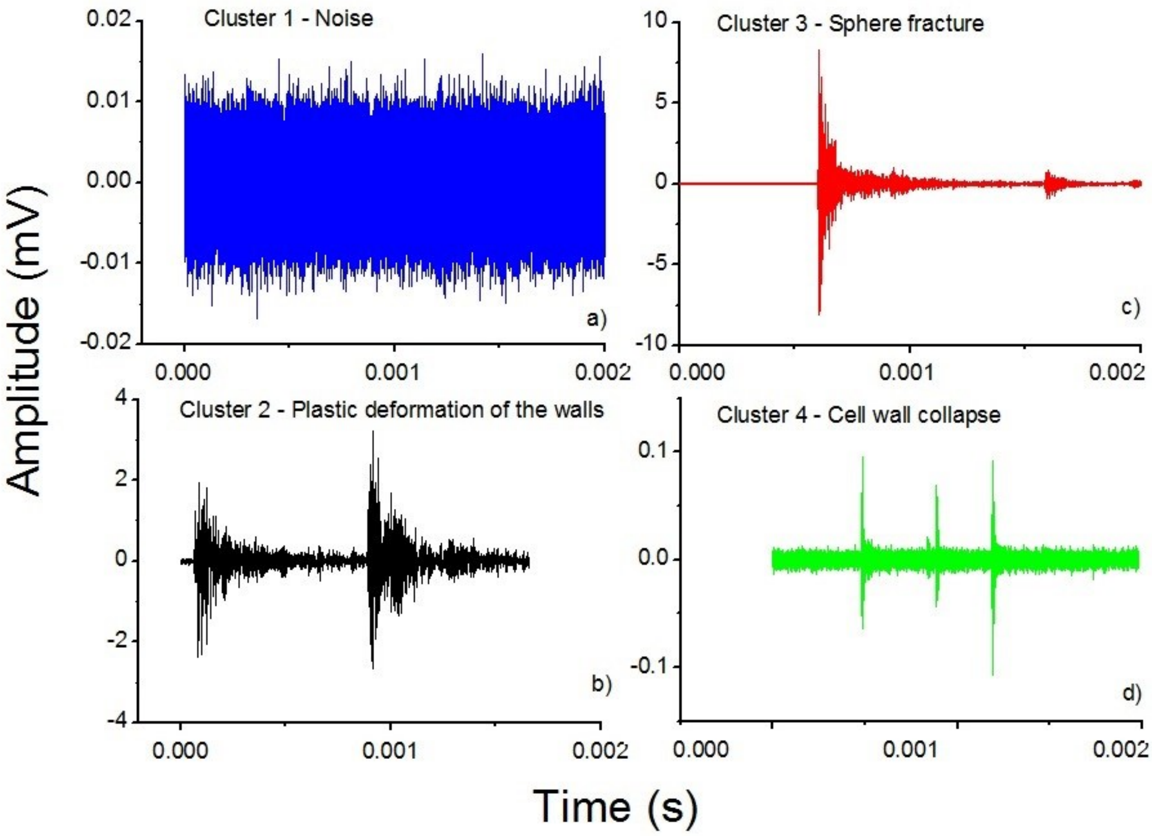

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