USE OF ACOUSTIC EMISSION ANALYSIS FOR MATERIAL-TESTING ALUMINUM FOAMS

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Abstract
Several aluminium foam materials were investigated with respect to the reversible maximum load limit. The edge between elastic and the start of plastic deformation and crack initiation under tension and compressive load was studied. Therefore the use of acoustic emission analysis (AEA) was successful by tested. Besides the adaption of AEA to the relevant material samples the sample shape had to be optimized. Finally it was possible to define critical values of service loads for different aluminium foam materials in several densities. A Coefficient was defined which could be used in combination with Ashby’s scaling laws to get a calculation of maximum stress levels of aluminium foams of different densities.

Keywords: aluminum foam, acoustic emission analysis, reversible load level

INITIAL CONDITIONS
The compressive stress-strain behaviour of aluminum foam has been sufficiently described [4-7]. Nearly every publication which introduces any kind of metallic foam shows the graph of the relationship between compressive stress and strain, with its typical material-and-density-dependent plateau shape (Fig.1).

![Graphical display of a compressive stress-strain curve.](image)

This characteristic diagram illustrates the level of stress at which irreversible deformation of the foam structure takes place for application as an energy dissipator. So far,
however, it has provided no information about maximum reversible load limits, and it is precisely this which is a particularly important reference parameter for the user. The effectiveness of an energy absorber must be absolutely reliable if it is to be used as a passive safety element. Thus, it is essential to preclude any damage resulting from irreversible deformation from arising during assembly, and during the period of use prior to the occurrence of any accidents or incidents causing damage.

In the case of conventional materials, one can more or less simply decide on $R_{p0.2}$ or $R_{p0.01}$, which also seems to be possible with aluminum foam at first glance. Experience has shown, however, that in range I of the stress-strain curve only a quasi-elastic initial range can be assumed and a comparable analysis is not possible.

**STATEMENT OF TASK**

From the discrepancy described above, we can derive the central question for the user: is it possible to determine a reversible deformation limit for aluminum foams?

**EXPERIMENT**

If elastically stored energy is irreversibly dissipated through the formation of cracks, plastic deformation etc., then acoustic energy must simultaneously be emitted. These acoustic signals can be recorded and analyzed using suitable measurement systems [8-9]. Using such a method, known as acoustic emission analysis (AEA), it appears to be possible to determine the maximum load limit mentioned above for aluminum foams.

To begin with, it is essential for the measurement task to first adapt the measuring system (testing probe, bandpass filter, decoupling, geometry of test specimen etc.). Using a self-designed probe, which is integrated into the lower pressure plate for compression tests, acoustic emission can be recorded and processed through a preamplifier, a bandpass filter and a final amplifier. The analysis is carried out on the basis of both the primary data (acoustic emission, force, deformation) and the secondary data (RMS value, pulse sum, pulse rate, trigger pulses, mechanical stress, elongation/compression).

**RESULTS OF EXPERIMENT AND DISCUSSION**

**Description and Adaptation of Experiment**

*Acoustic Emission Measuring System*

The setup of the acoustic emission measuring system is shown in Fig.2. The cumulative sampling rate of 800 kHz ensures that the acoustic data will be stored at a sampling rate of 400 kHz if the resolution is sufficient. The other specified measurands can be seen in Fig.2.
Fig. 2. Basic setup of the acoustic emission measuring system.

The acoustic decoupling is achieved through a series of preliminary experiments using a compression-rigid but acoustically insulating combination of MDF sheets and a cardboard –silicone composite (silicone-cardboard). The acoustic decoupling of the test specimen and the measuring equipment can be verified by the pencil test defined in standard EN 1330-9.

**Geometry of Test Specimen**

In addition to the adaptation of the measuring system, the geometry of the test specimen must be optimized. For a correlation of acoustic signals with damage mechanisms, it is advantageous to use an indented test specimen. This predetermines the damage zone and simplifies the analysis. An important side effect also results for the reproducible distance between the acoustic source and the acoustic probe. In a cross comparison, round notch geometry produced the best results when compared to various pointed indentations. Analogous comparative optical stress measurement tests confirm the results (Fig.3).
Compression Test and Kaiser-Effect in General

The functioning of the measuring system can be confirmed by the use of compression-deformation tests over the entire deformation area as well as the measurements of the Kaiser-Effect [10-11].

Measurements carried out on various aluminum foam alloys show their respective characteristic acoustic emission behaviour. Brittle materials are characterized by a high degree of acoustic activity with numerous individual burst signals, ductile foams on the other hand display little acoustic activity. An example of these measurements can be seen in Fig.4, where the test data for measurements over the entire deformation area for the foam material AlSi7 are shown.

The Kaiser-Effect describes the acoustic behaviour of test specimens that give off no acoustic emissions whatsoever upon load release from the plastic deformation range provided that a previously reached maximum stress level is not exceeded. This can be demonstrated to occur in deformation range I for foams.
Fig. 4. AE measurement of an AlSi7 test specimen (density 0.3 g/cm³ - display of the acoustic emission data (above), the stress-strain curve, the pulse sum-strains curve, and the acoustic energy-strain curve (middle) and the RMS value of the acoustic emission data (below).

However, as soon as the compressive stress plateau becomes distinctly pronounced, acoustic activity becomes perceivable during the load release cycle. This suggests an internal friction inside the deformed cell membranes and illustrates that the assignment of a coefficient of elasticity at some 20% or 25% deformation as proposed by various authors is misleading. A statement can only be made in this case about a coefficient of deformation at x% compressive stress.

**Tensile Test**

The results of the Kaiser Effect show that under compression strain, plastic deformation, crack formation etc. overlie each other. In order to be able to observe individual mechanisms, it would be beneficial to gain information from acoustic emissions and hence the damage behaviour of aluminum foams through tensile tests.

The configuration of the test specimen assumes an AFS (aluminum foam sandwich) that can be tested through the covering sheet by friction locking in a conventional clamp. The acoustic decoupling, in turn, is realized through silicone-cardboard. By using a milled off covering layer in the middle area between the fastening bolts, a damage zone is defined, analogous to pressure tests (Fig.5).
Acoustic emission which is recorded during the experiment clearly shows burst signals which directly indicate crack formation and crack growth in the cell structure. Grinding noises, i.e. characteristically continuous acoustic emissions, do not occur in this test. The individual acoustic signals correlate to the stress-strain curve.

**Correlation Acoustic Signal – Damage Mechanism**

Using an iterative procedure, test specimens are placed under stress several times both in tensile tests and compression stress tests. The surfaces of the test specimen in the area of the macroscopically applied indentations are scanned and can thus be compared to the original condition after every stress load. This makes possible the detection of the kind of damage (plastic deformation, formation of cracks, friction between broken cell membranes). As an abort criterion for the individual load cycle, a displacement-controlled method or an acoustic signal triggering is possible, depending on the experiment being conducted. As an acoustic signal triggering, the level of 1 V of the RMS value at an overall amplification of 47 dB turns out to be ideal.

The comparison between tensile test and compression test data reveals a shorter rise time and fall time in the case of the tensile test. This describes the process of a tensile test, which is characterized less by plastic deformation than by cell membrane cracking and crack growth. In the case of a compression test, it is more the overlay of plastic deformation that is recorded, mainly the bending load in the gaps between the cells, to the longer rise and fall time of the individual acoustic signals.

Using these results, the trigger thresholds for a focused examination of individual damage levels can be defined. Foam structure data, for example cell membrane geometry which takes on a certain form depending on the respective alloy, can be correlated to the acoustic data. Doing so will make possible the definition of the optimal load-bearing foam structure, founded upon the results to be shown below; and it will be based on foam qualities which are currently realizable with existing manufacturing technology.

**Reversible Load Limits for Aluminum Foams**

To begin with, the determination of a reversible load limit is oriented toward a compressive stress-strain plateau (range II of the compressive stress-strain curve) or the tensile-strength level, which is generally well known among experts. Both of these can be mathematically described as a function dependent on the density and the respective specific
value of the solid material (formulas 1 and 2) [3; 12]. Fig. 6 illustrates these levels as a function dependent on the respective aluminum foam and the foam density using performance data.

\[
\sigma_{pl} = 0.2 \cdot \sigma_{ys} \left[ \left( \frac{\rho}{\rho_s} \right)^{1.5} + \left( \frac{\rho}{\rho_s} \right) \right] 
\]

(1)

\[
\sigma_{\text{Tensile}} = (1.1 \ldots 1.4) \cdot \sigma_{\text{Compression}} 
\]

(2)

Fig. 6. Tensile strength (left) and plateau stress (right) as a function of foam density and foam alloy type. The tensile strength data includes a comparison to values from source references.

The load limits for the respective aluminum alloys are determined on the basis of these underlying data. These characteristics, which are generally comprehensible and mathematically easy to calculate, represent a level of 100% in the following discussion. The tensile strength or plateau stress corresponds to a value of 100%.

The correlation of acoustic emission and damage mechanism described earlier makes the definition of a trigger threshold possible, which describes the irreversible damage of the foam structure as a criterion. This becomes the case as soon as a significant acoustic emission event is detected during the tensile strength or compression test, and the RMS of this signal exceeds the trigger threshold of 1 V (47 dB of overall amplification).

Taking these compiled data as a basis, a limit value can be calculated in accordance with the example presented in Fig. 7 after testing a large number of test specimens. The 100% level for the tensile and compression load as well as the curve which corresponds to the reversible load limit for the material AlSi7 are displayed to serve as an example.
Fig. 7. Tensile strength (left) and plateau stress (right) and the respective level of the first characteristic acoustic emission event as a function of the specific density for the foam material AlSi7.

For the purpose of simplified illustration, the level equivalent to 80%, 60% etc of the plateau level can be described using isolines based on the plateau level (100%). The reversible deformation limit ascertained from the acoustic data can thus be interpreted in a direct comparison more easily, and implemented by the user in a simpler manner (Fig. 8 and Fig. 9).

Fig. 8. Plateau stress and strength level at a trigger threshold of the RMS signal of 1 V for the material AlSi7 (for orientation, isolines with 80%, 60% and 40% of the plateau stress level are shown).
In summary, the following levels resulted from the various stress loads examined and different aluminum materials and can be seen in Table 1 below.

Tab.1. Coefficients for use in the Ashby scaling law to calculate the reversible load limit

<table>
<thead>
<tr>
<th>material</th>
<th>AISi7 tensile*</th>
<th>AISi7</th>
<th>Al99.7</th>
<th>AlMgSi</th>
<th>AlSi12</th>
<th>AlSi6Cu4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_{1.\text{AcousticEvent}}/\sigma_{pl}$</td>
<td>70 %*</td>
<td>43 %</td>
<td>70 %</td>
<td>52 %</td>
<td>43 %</td>
<td>52 %</td>
</tr>
</tbody>
</table>

*Tensile strength as a basis [MPa]

With regard to the reversible deformation limit of AISi7, a significantly higher load limit for tensile loads stands out when compared to that for compression loads. Although a similar relative level results for AlSi6Cu4 initially, the highest absolute value is recorded for this material due to its high compressive strength.

CONCLUSION

Starting with the known stress plateau data, the 10 density specific stress plateau levels depicted in Fig.10 result for the foam materials examined. Among the tested alloys, the foam material AlSi6Cu4 displays the highest level.
Fig. 10. Plateau stress of the foam materials Al99.7, AlMgSi, AlSi12, AlSi6Cu4 and AlSi7 as function of density (Regression diagram according to the Ashby approach).

As has been described, acoustic emission analysis makes it possible to detect and characterize irreversible processes in foam test specimens. After evaluating the acoustic emission data, the stress levels shown in Fig. 11 can be designated as reversible deformation limits for foam materials.

Fig. 11. Maximum load ranges for the tested aluminum foam alloys under compressive stress as a function of density (compressive stress level at the first characteristic acoustic signal).
In conclusion, it turns out that the sparse results which exist about the fatigue strength levels of aluminum foam materials can be compared with the load parameters shown in Fig.11, and actually even provide a good conformity. Thus, acoustic emission testing on foam components is principally to be classified as feasible and significant. As a passive measuring method, it can be adapted for further experiments or integrated as an assembly aid for detecting possible pre-existing damage to the foam structure.

REFERENCES