ACOUSTIC EMISSION RESPONSE OF METCOMB FOAMS DURING INDENTATION

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The effect of the composition of the cell-wall material on the deformation behaviour of Metcomb® metallic foams was investigated. The acoustic emission (AE) response of different aluminium-based foams was recorded during indentation and evaluated with respect to the composition of the cell-wall material. The AE parameters revealed changes in deformation mechanism with increasing silicon and magnesium content in the cell-wall material.

Key words: metal foam, indentation, acoustic emission

AKUSTICKÁ EMISE PĚN METCOMB V PRŮBĚHU INDENTAČNÍCH ZKOUŠEK

V práci je studován vliv složení materiálu stěn buněk na deformační chování kovových pěn Metcomb®. Odezva akustické emise (AE) byla monitorována v průběhu indentačních zkoušek různých kovových pěn na bázi hliníku a vyhodnocena jako funkce složení materiálu stěn buněk. Výsledky dokumentují změnu deformačního mechanismu s rostoucím obsahem křemíku a hořčíku v materiálu stěn buněk.

1. Introduction

Nowadays, metal foams, in particular those made with aluminium alloys, become more and more important as lightweight construction materials for the automotive and aerospace industry [1]. The design of foam parts challenges the controlling of the manufacturing process of aluminium foams. In the past few years

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several different processing routes have been revisited and new investigations have been done to achieve a homogeneous cellular structure [2–4]. One of the newest processes leads to the so-called Metcomb® foam, which shows potential for applications in industry since it has a relatively narrow cell-size distribution and foam parts with a tight surface skin can be produced as well. The cell-wall material in this type of foams is an aluminium matrix composite reinforced by Al_2O_3 or SiC particles.

The fabrication of Metcomb® foam is a quite new technique, and only a few investigations, like the effect of the particle content and the constitution of the matrix on the stability and cell-wall thickness [2, 5–6] were performed on them. Up to now only a few experiments were carried out to examine the mechanical behaviour of this kind of foams [7], and the effect of the alloy composition on the strength and deformation processes was not yet investigated.

Acoustic emission (AE) stems from transient elastic waves generated within the material due to sudden localized irreversible structure changes (see e.g. [8] for reference). Therefore, AE is a promising technique to investigate the deformation processes in metal foams during deformation. Up to now, only compressive properties of aluminium foams were investigated by AE [9, 10] and the AE responses of Alporas and Alulight foams during indentation have also been monitored [10]. The indentation was found an appropriate technique to investigate deformation mechanisms, since the deformation takes place in a small volume.

The objective of this paper was to investigate the particular mechanisms which control the deformation of the foam subjected to indentation. Special attention was devoted to the influence of Mg and Si content. To separate individual mechanisms which may occur at different stages of the deformation process, indentation tests on individual foam cells were applied with *in situ* monitoring of AE parameters.

2. Experimental procedure

Series of Metcomb® foams were investigated. During the fabrication process blowing gas is injected into an aluminium melt of Al_2O_3 or SiC particulate reinforced aluminium matrix composite at a temperature of about 700 °C. The gas, usually air or oxygen, blows up the melt and the resultant mixture of bubbles and melt (liquid foam) floats up to the surface of the melt, from where it is guided into a mould. Finally, the liquid foam is allowed to solidify. The cell-size and the density can be controlled through adjusting the pressure and the flow rate of the blowing gas [2].

In our case, the blowing gas was air and the aluminium matrix was an AA6061 (AlMg1Si0.6CuCr) aluminium alloy to which different amounts of silicon and magnesium were added (Table 1), containing 15 vol.% Al_2O_3 particles of 16 μm average size. The average cell-size and the relative density of the fabricated foams were almost independent of the composition of the matrix alloy: the average cell-diameter

Table 1. Si and Mg concentrations added to AA6061 (AlMg1Si0.6CuCr) + 15 vol.% Al_2O_3 particle reinforced composite base material

	Si0.6	Si2	Si5	Si10	Si10Mg2	Si10Mg5	Si10Mg10
Si [wt.%]	0.6	2	5	10	10	10	10
Mg [wt.%]	0	0	0	0	2	5	10

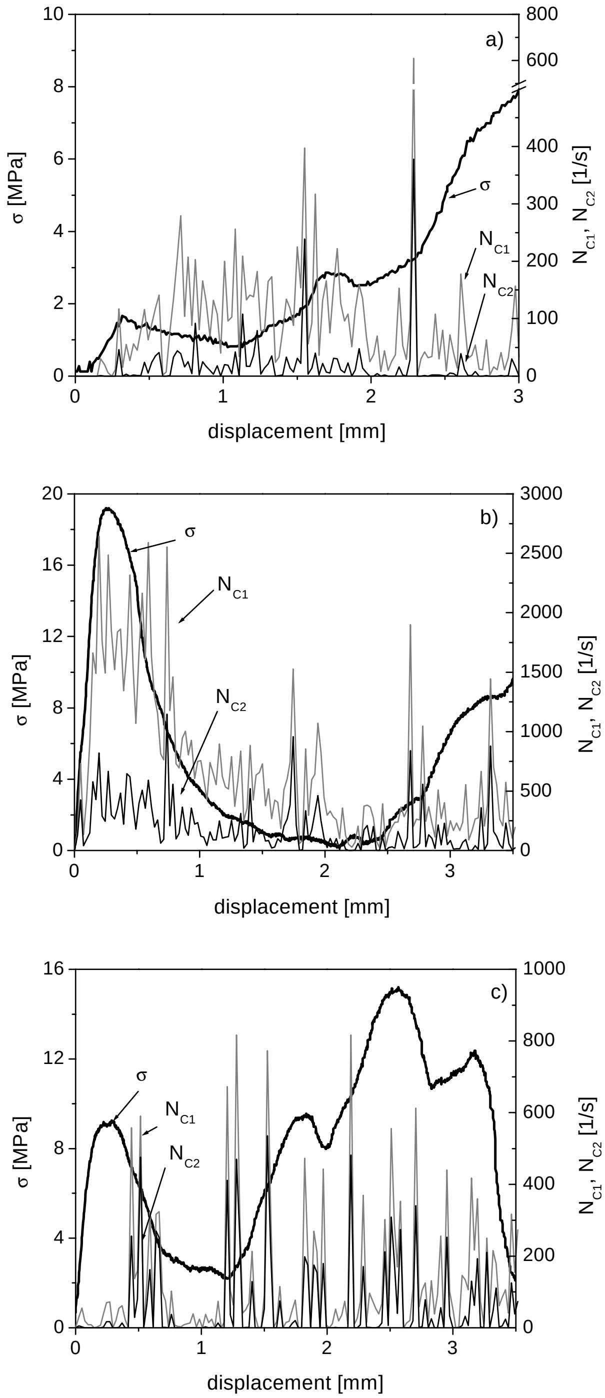
was between 4 and 6 mm and the relative density was between 11 and 14 % for each sample.

To investigate the effect of the silicon and magnesium content on the deformation mechanisms, indentation tests were performed on rectangular samples with dimensions of about 30 × 30 × 20 mm^3. Three indentations were carried out on each sample, and one of the three indentations was performed on a relatively denser area. All indentations were made at a distance of at least 2 indenter diameters away both from previous indentation locations and from free edges. The diameter of the flat-plate circular punch was 5 mm. The indentation tests were performed with an MTS hydraulic machine at 0.025 $mm \cdot s^{-1}$ constant indentation velocity. The indentation depth was determined from the crosshead displacement.

A computer controlled DAKEL-XEDO-3 AE system [11] was used to perform monitoring (two-threshold-level detection recommended by an ASTM standard [12]) and full analysis of AE signals during indentations. An LB 10A standard AE transducer (almost flat response in a frequency band from 100 to 600 kHz) was attached to the specimen surface with the help of creep-resistant silicon grease and a spring. The AE signal was evaluated in two channel units (hereinafter slots 2, 3), simultaneously. The total gain was 90 dB for the slot 2 and 70 dB for the slot 3, respectively. A comprehensive set of AE parameters involving count rates at two threshold levels, AE rms voltage, AE event parameters and signal waveforms were evaluated. The AE signal sampling rate was 4 MHz, the threshold voltages for the total AE count N_{C1} and for the burst AE count N_{C2} were 750 and 1450 mV, respectively. Selected AE signal waveforms were saved through transient recording for subsequent evaluation. Further detail on the investigated parameters can be found elsewhere [13].

3. Experimental results and discussion

Indentation tests were performed on Metcomb metal foam with different silicon and magnesium content. The reproducibility of the deformation curves is rather poor, since the diameter of the indenter was less than six times the average cell diameter which is a condition for good reproducibility [14]. Nevertheless, the deformation curves show common characteristics; following a quasi-linear stage the stress increases further, and after reaching a maximum value (peak stress) it drops gradually until it becomes lower then about half of the peak stress (Fig. 1). Then,



a)
σ [MPa]
N_{C1}, N_{C2} [1/s]
σ
N_{C1}
N_{C2}
displacement [mm]
b)
σ [MPa]
N_{C1}, N_{C2} [1/s]
σ
N_{C1}
N_{C2}
displacement [mm]
c)
σ [MPa]
N_{C1}, N_{C2} [1/s]
σ
N_{C1}
N_{C2}
displacement [mm]

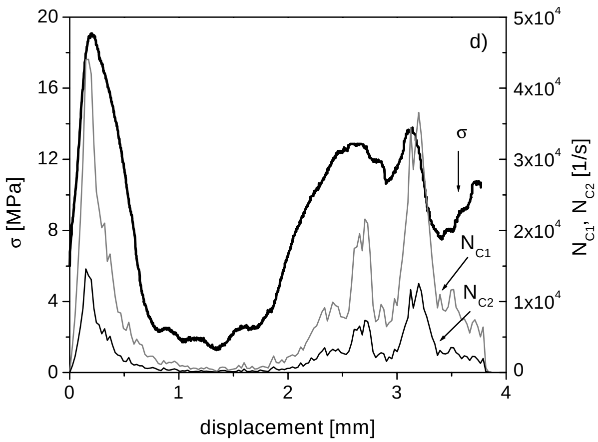


Fig. 1. Stress-displacement curves (thick line) with the count rate curves of slot 2 during indentation into (a) Si0.6, (b) Si10, (c) Si10Mg2 and (d) Si10Mg10. The grey and the black lines are the measured N_{C1} and N_{C2}, respectively.

again, the stress oscillates, causing wavy deformation curve. The measurements show that the peak stress depends on the silicon and magnesium content of the cell-wall material and on the relative density of the foam beneath the intender. Increasing the Si content of the cell-wall just like increasing the Mg content increases the peak stress, while the addition of 2 % Mg to Si10 softens the cell-wall material. The local relative density also modifies the peak stress. If the indentation was performed in a dense area, then the initial quasi linear stage was relatively long and the stress increased steeply. During this stage the AE response was very weak, if any, except for the case of the Si10Mg10 sample. As the stress increased further, following the linear stage, usually there was a peak in N_{C1} (slot 2). After the stress maximum, a high energy signal reflecting fracture of cell wall(s) was measured both in the N_{C1} and in the N_{C2} (slot 3). Since beneath the dense part of the foams there is usually a pore, after the initiation of cracks at the perimeter of the indenter the stress drops to almost zero. If the indentation was performed on a less dense area (e.g. on the junction of cell-walls or on a cell-wall), first the cell-walls bend and then they fracture (Fig. 2b). As the broken cell-walls reach other cell-walls just beneath the intender, the stress increases and the fracture of these already broken cell-walls is the source of AE (Fig. 2c).

Count rates at two threshold levels, event rates and selected AE signal waveforms at two different total gains (70 dB and 90 dB, respectively) were recorded to examine the effect of the Si and Mg content of cell-walls. The N_{C1} and N_{C2} dependences of both slots consist of many peaks. While at high Mg or Si contents

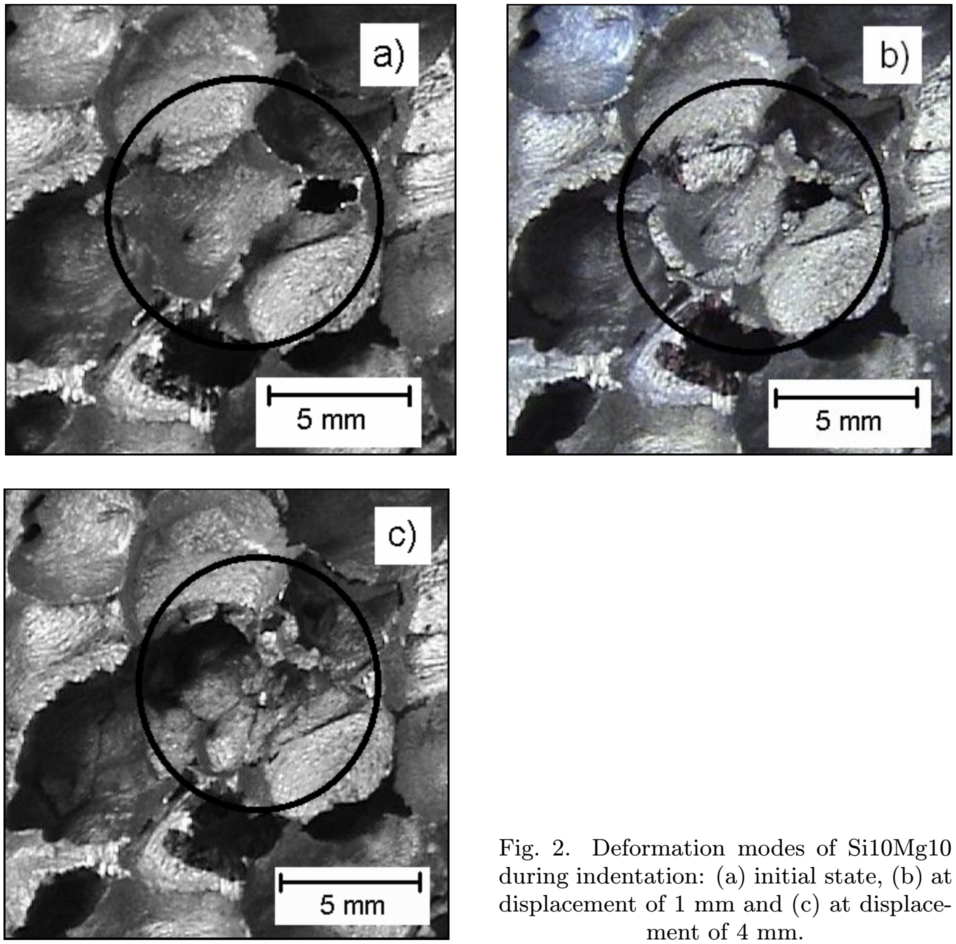


Fig. 2. Deformation modes of Si10Mg10 during indentation: (a) initial state, (b) at displacement of 1 mm and (c) at displacement of 4 mm.

high peaks (bursts) of slot 3 (total gain 70dB) in AE response are recorded at maxima in the stress, at low Mg or Si contents AE bursts were obtained even at the stress minima. This suggests that there is a change in deformation mechanism as the magnesium and the silicon content is increased.

In the case of the Metcomb® foams the AE signals can be classified into three groups according to their waveform: waveform A, B and C. Waveform A and B have a simple structure; in waveform A (Fig. 3a) the amplitude is increasing, than it is decreasing, while in waveform B (Fig. 3b) the rise time is negligible. There are also more complex waveforms (Fig. 3c). Here the beginning of waveform looks like A or B-type, but the signal drops rapidly, and then it starts to increase and decrease again, results in a plum-stone-like shape of the waveform. Usually, these three types overlap. By investigating selected waveforms of slot 3 we found that in the case of Si10Mg10 the waveform is typically of type B with very short decay

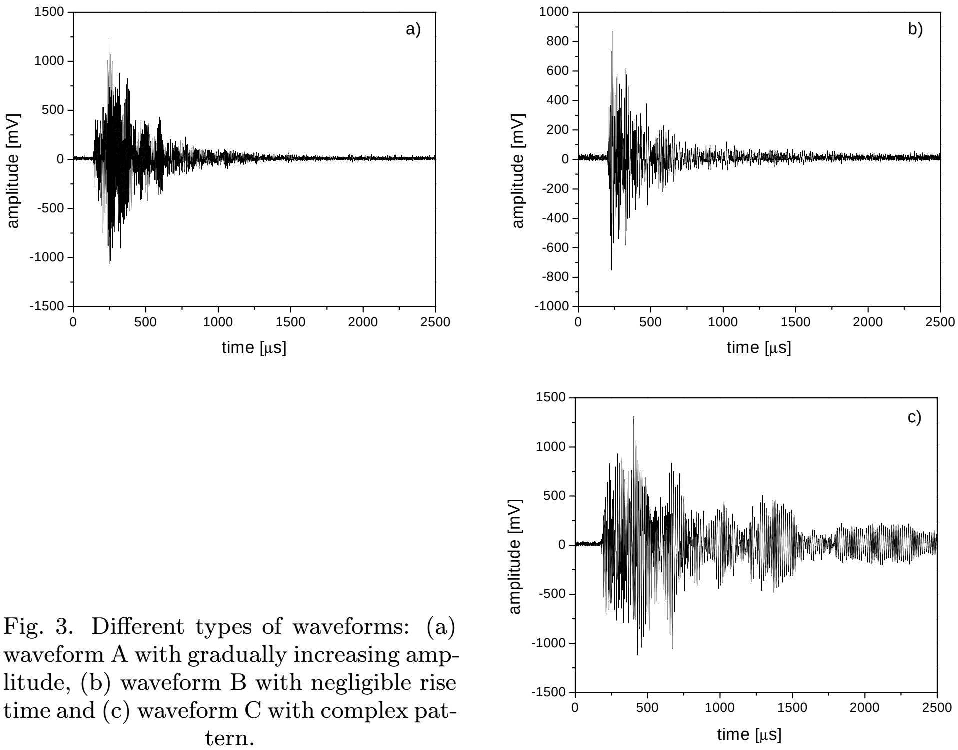


Fig. 3. Different types of waveforms: (a) waveform A with gradually increasing amplitude, (b) waveform B with negligible rise time and (c) waveform C with complex pattern.

time of about 750 μs after reaching the maximum voltage. In all cases most of the signals were B or C-type, which indicates that the main deformation mechanism is not plastic yield, especially in the case of foams with high Si or Mg content.

To characterize the Metcomb® foam in terms of the deformation behaviour, new AE parameters are introduced. The average values of N_{C1} and N_{C2} are the sums of N_{C1} and N_{C2} divided by the time, respectively; the average event rate is the event sum divided by time; the average rms voltage and finally the maximum of N_{C1} and N_{C2}. As Fig. 4 shows, the average values of N_{C1} and N_{C2} and the maximum of N_{C1} and N_{C2} as well as the average event rate and the average rms voltage of slot 2 are increasing with increasing Si content, however, this trend is not pronounced for Si content less then 2 %. Likewise, with increasing Mg content, the average values of N_{C1}, N_{C2}, AE events, the rms voltage and the maximum N_{C1} and N_{C2} of the slot 2 increase. It was found that Si10Mg10 exhibits the highest maximum and the highest averaged values; the average event rate and the average and maximum values of N_{C1} and N_{C2} are by an order of magnitude higher than those of the others. Adding 2 % of Mg to the cell-wall material of Si10 causes a marked decrease in the averaged N_{C1}, N_{C2} and event rate and, also, in the maximum N_{C1} and N_{C2}.

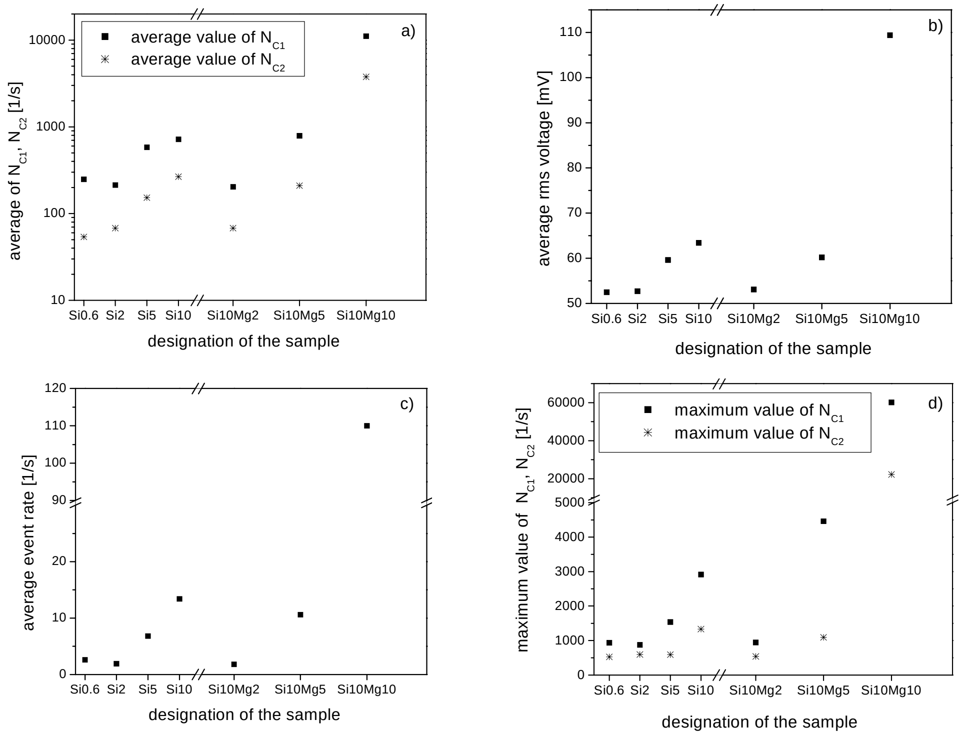


Fig. 4. (a) Average value of N_{C1} and N_{C2}, (b) the average rms voltage (c) the average event rate and (d) the maximum value of N_{C1} and N_{C2} as a function of the Si, Mg content of the cell-wall material.

The AE results are in agreement with the anticipated changes in the mechanical behaviour as the composition of the cell-wall is changed. In aluminium-silicon system increasing silicon content increases the hardness and the strength and decreases the plasticity of the aluminium matrix [15]. Increasing magnesium content also influences the strength of the cell wall; whereas hardness and strength increase, the ductility decreases. At approximately 12–14 % of magnesium, the alloy becomes very brittle [15]. In the aluminium-magnesium-silicon system Mg_2Si precipitates form usually, especially, in alloys with more than 3–4 % magnesium. Also on the surface of the Al_2O_3 particles the formation of $MgAl_2O_4$ spinel was observed in Al-Mg-Si composites reinforced with alumina particles [6, 16]. Both Mg_2Si and $MgAl_2O_4$ increase the brittleness of the cell-wall material. Since brittle fracture is anticipated to produce a larger AE signal, brittle fractures should give a significant contribution to the AE count rates. This results in increasing AE averaged values (average value of N_{C1} and N_{C2}, average event rate and the average rms voltage) with increasing silicon and magnesium content, respectively. The average values of the different AE parameters also reveal, that adding 2 % Mg to Si10 changes the deformation mechanisms; the cell-wall material becomes less brittle and Si10Mg2 tends to deform by plastic deformation, in contrary to Si10. This is confirmed also by the fact that while at Si10Mg2 high peaks in N_{C2} of slot 3 in AE response were obtained at the stress minima. In the case of Si10 AE bursts are recorded rather at the maxima in the stress, indicating that reason for stress drop in the case of Si10 is the fracture of cell walls.

4. Conclusions

The AE response of Metcomb® foam during indentation was examined with respect to different cell-wall compositions. New AE parameters were suggested to describe the effect of the silicon and magnesium content. These parameters allow us to conclude that with increasing Si and Mg content brittle fracture becomes increasingly dominant in the deformation. Also the coincidence of high, burst peaks in AE and the maxima of stress at sample with high Mg or Si contents suggests that the reason for the stress drop during indentation is the brittle fracture of the cell-walls. By analyzing the waveforms of Si10Mg10 and taking into account the extremely high maximum and average AE values we suggest that the deformation mechanism changes for the case of Si10Mg10, however, further investigations are needed for more detailed explanations.

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