

## *Sound Absorption Ability of Aluminium Foams*

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**Abstract.** The sound absorption ability of metallic foams is discussed with respect to the preparation method of foam, material composition, foam porosity, thickness, structure, and various treatments to make the foam structure permeable for sound. Both powder metallurgical route prepared foams and melt route prepared foams were studied. It was observed that the sound absorption properties of metallic foams depend predominantly on the foam porosity and opening of its structure and only after that on the properties of foam cell wall material itself.

### 1. Introduction

Absorption of sound is very important due to minimizing of noise arriving from insides to outside – gym, offices, music, applause etc. and reversely – sound from cars, airplanes, industrial companies etc. This sound is absorbed by materials used for sound-absorption applications. For example: mineral wool, plastic acoustic foams, wooden acoustic material, and bituminous felt. Each type absorbs the sound in different way. Mineral wool and plastic acoustic foam are porous absorbers and absorb the sound by viscous losses mechanism due to friction when vibrating air molecules are forced through the pores and interact with a fibres or pore walls. These absorbers are good for absorption of high frequencies [1].

Wooden acoustic materials work on principle of cavity absorbers also know as Helmholtz resonator. It is simple container with narrow neck – the air within the cavity has a spring-like effect at the particular resonant frequency  $f$  which can be adjusted by hole diameter and distance between the holes in following way (at constant speed of sound  $v$ ):

The third type is bituminous felt is a membrane absorber mounted at some distance from the front of a solid wall. It is a resonant system formed by mass-spring combination of the facing sheet/panel and the stiffness of enclosed air. Membrane absorbers are most effective at low frequencies.

There are various disadvantages of above mentioned absorption materials mostly due to their material origin: The mineral wool can't be used in humid environment, is not self bearing due to shedding of the fibres; polymeric foams can't be used in flammable environment as well as bituminous felt or wooden cavity absorbers. All above mentioned materials have also limited

durability and difficult recyclability (besides wood). Very often they are combined together to absorb as wide as possible frequency range. Various aluminium and stainless steel perforated cover sheets are typically used as load bearing panels in combination with sound absorbing materials, especially mineral wool. However certain thickness of sheets is necessary to be self bearing and to support also the mass of sound absorbing material. All of this increases not only the costs but also the weight of absorbing material per square meter.

Hence usually there is enough space at building industry the specially arranged thicker aluminium panels made from aluminium foams [2-5] can be successfully used instead of simple aluminium and steel sheets at constant or even less weight. The unique cellular structure is the reason that at constant weight the aluminium foam panel is stiffer and stronger. Moreover, aluminium foam can be used in reactive and humid atmosphere, is fire resistant, has a long durability, good recyclability, is self-bearing and its porous structure offer certain degree of good sound absorption ability. From this reason is aluminium foam already industrially used in sound absorbing panels (see Fig. 1).



Fig. 1. Alporas aluminium foam sound absorption panels next to roads (left) or as buildings insulation (right) in Japan [6].

Aim of the work is to review the aluminium foams sound-absorption properties [7-15] with respect to the preparation method of foam, material composition, foam porosity, thickness, structure, and various treatments to make the foam structure permeable for sound.

## 2. THEORETICAL BACKGROUND

The sound absorption properties of aluminium foams significantly depend on the method of preparation (see Fig. 2). Three different types of aluminium foams are investigated in this work: ACCESS, ALPORAS and ALULIGHT. Each type of foam is produced in different way leading to different porosity, pore structure and permeability to sound waves. In order to better understand the possible use of aluminium foam as sound absorber it is therefore necessary to mention briefly also the methods of foams preparation.

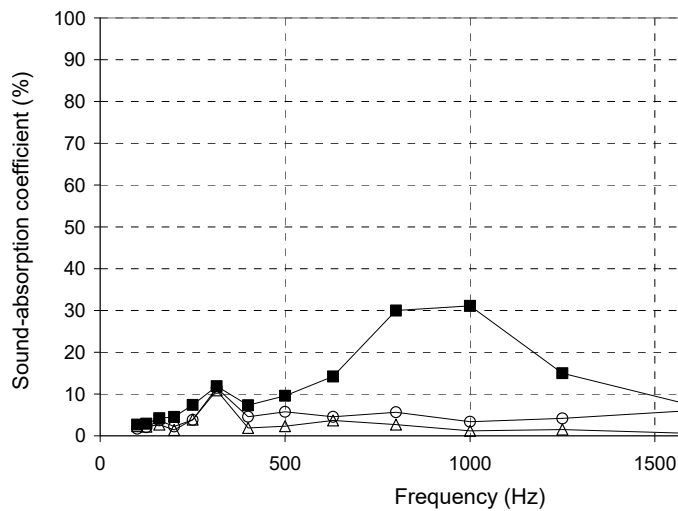


Fig. 2. Sound-absorption ability of as received aluminium foams made by various preparation methods placed directly onto rigid wall (various porosity, various pore size, almost constant thickness, with/without surface skin).

### ACCESS

ACCESS "cellular" material with open pore structure is made via negative pressure infiltration using a pre-form consisting of soluble spherical particles [10-12]. Manufacturing process in hand with pore structure is presented in Fig. . The container is filled by soluble particles and is preheated; the liquid aluminium is then poured to the container and it infiltrates around preheated particles under negative pressure. After cooling, the particles are leached out and porous aluminium is made. This process is very simple and allows easy modification of pore size only by changing the particle diameter. The constant, bimodal or gradient pore size can be achieved if spheres of different diameters are filled to required sample thickness. However; the ligaments between simple cells are thick so the foamed material would be rather heavy which limits this type of metallic foam to be used mostly as self-bearing part of construction.

### ALPORAS

Manufacturing process in hand with pore structure is presented in Fig. 4. The  $TiH_2$  called also "blowing agent" is added into aluminium melt as a source of foaming gas. It is necessary to customize the melt due to stabilizing the arising gas bubbles before addition of blowing agent. For this purpose, the calcium which creates small oxides and complex phases with aluminium in the melt during stirring at elevated temperature is used. After the melt is stabilized, the blowing agent which releases hydrogen gas in the hot viscous liquid is added into melt. The melt soon starts to expand and gradually fills the foaming vessel. After cooling down the vessel below melting point of the alloy, the liquid foam turns into solid aluminium foam and can be taken out of the vessel for further processing [2-4]. Such a foamed aluminium is made in a huge blocks of dimensions  $2400 \times 750 \times 400$  mm from which the smaller parts can be easy machined out – there is no surface skin covering the pore structure of these parts. No surface skin in hand with very thin ligaments interconnecting the pores (pore faces) means that *thin structure* made from this foam lacks self-bearing and needs to be improved by using an Expanded Metal Sheet (EMS) or by making a sandwich panels using sheets (usually aluminium) which are bonded together with foamed core. There is no easy modification of the pore structure (porosity) if foam is produced in such a big

blocks; but it slightly changes through the block spatial as a result of manufacturing process. It means that certain modification of pore structure can be achieved [13].

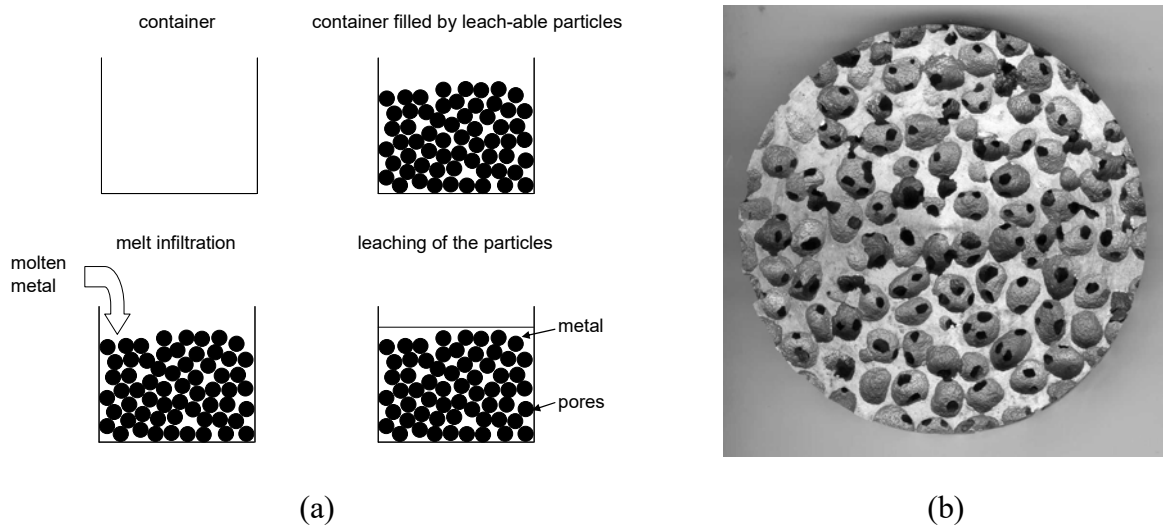


Fig. 3. (a) Manufacturing process of ACCESS open „cellular“ material and (b) open pore structure with a thick ligaments between adjacent pores.

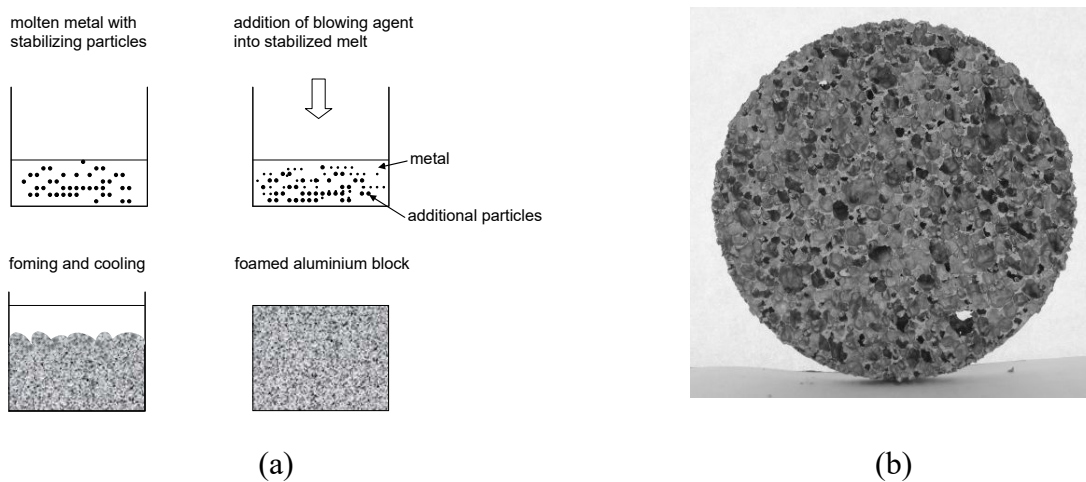


Fig. 4. (a) Manufacturing process of ALPORAS foam and (b) semi-open cellular structure with a thin pore faces interconnecting adjacent pores.

### ALULIGHT

Manufacturing method of ALULIGHT foam shown in Fig. 5 consists of mixing of aluminium powder together with blowing agent powder and some alloying elements followed by cold isostatic compression and hot extrusion. This way, a foamable precursor is prepared in which the blowing agent is gas-tightly embedded into the metal matrix without any notable porosity. Foamable precursor is subsequently placed into a mould of predefined shape and heated up to mushy state upon which the blowing agent releases hydrogen and expands semi-liquid viscous aluminium into a highly porous structure. Finally, the foam is rapidly cooled to prevent the collapse of the foamed structure. The result is 3-D shaped foamed component with a continuous surface skin and a closed cellular internal structure. Continuous surface skin assures self-bearing of the foam and

manufacturing process provides easy modification of the pore structure (porosity) only by different filling of the mould with foamable precursors [5]. This manufacturing process doesn't need to be stabilized by ceramic particles due to presence of very thin oxides covering powder surfaces [9].

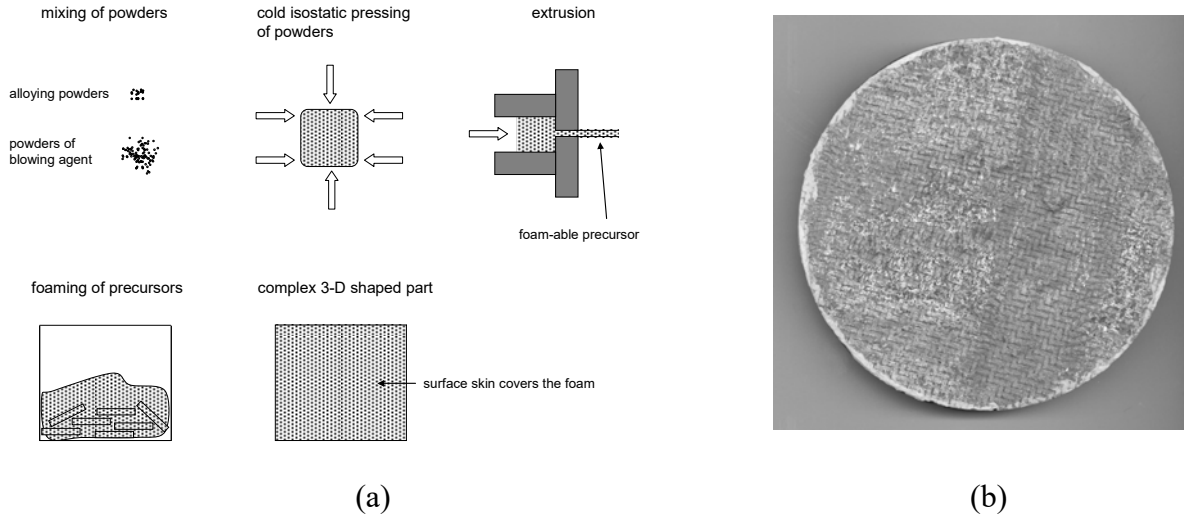


Fig. 5. (a) Manufacturing process of ALULIGHT foamed material and (b) closed cellular structure covered by surface skin.

### 3. Sound absorption of metallic foams

Absorption mechanism of the foam manufactured via negative pressure infiltration ACCESS process is described in [4] and works on principle of entering the sound to open structure. Sound enters the structure and vibrates internal strands, thus acoustic energy is absorbed by dissipation on the vibrating strands. Guiping et al. [14] investigated that more sound energy is dissipated within the structure and absorption ability is improved when pore size per unit area increases. Increasing pore size per unit area is achieved by decreasing of granule diameter during manufacturing. Sound-absorption ability depends on porosity as well. If porosity is too low, the sound wave is mostly reflected. If porosity is too high the sound wave penetrates the structure and absorbed energy decreases. The ideal porosity for good sound absorption was estimated experimentally to be 75-80 %. Guiping et al. also revealed that absorption ability can be improved by increase of sample thickness due to longer travel distance of the sound [14].

Contra-ordinary to Guiping et al. work, where mechanism of sound absorption is described via vibration of the strands; Han et. al. explain in their work [10] that pore structure is too stiff for strands vibration and absorption ability depends mostly on flow resistivity of the structure. Flow resistivity which is governed by pore size and holes interconnecting them depends also on sample thickness. To absorb sound at the lower frequency the air gap should be applied between the structure and rigid wall. Applying the air gap invoke a cavity or Helmholtz resonator absorption mechanism with a resonant frequency according to equation

$$f_r = \frac{c}{2\pi} \sqrt{\frac{A}{LV}}, \quad (1)$$

where  $c$  is velocity of the sound,  $A$  is cross-sectional area of the neck,  $L$  is neck length and  $V$  is volume of the cavity.

If pore size is too low (0.5 mm and below) absorption is preliminary lead by viscous losses and no cavity resonator mechanism occurs due to high flow resistivity of the structure. If the pore size is

higher (1.5 - 2.5 mm) the cavity resonator takes place due to lower viscous losses contribution and ability to sound wave transit the structure. However, the sample with smaller pores can be adjusted to cavity resonator mechanism if thickness is lower than in case of sample with bigger pores. Increasing air gap behind the sample moves sound-absorption coefficient to lower frequencies with no changes within the absorbed frequency range above 50% of sound absorption coefficient. Also if sample thickness increases, the absorption ability of foamed structure increases due to increase of the flow resistance which is in agreement with [12] and [14].

Influence of pore size, pore openings, porosity and air gap between the foam and rigid wall to sound absorption ability is described in work of Lu et al. [11] according to analytical model. It was considered that the absorption mechanism is via viscous losses.

$$\alpha = \frac{4R/\rho_0 c_0}{\left(1 + R/\rho_0 c_0\right)^2 + \left(M/\rho_0 c_0\right)^2} \quad (2)$$

where  $\rho_0 c_0$  is internal resistance of air,  $R$  is real part of impedance and  $M$  is imaginary part of impedance.

Lu et al. found that absorption ability of the pore structure increases with decrease of the pore size [11], as reported also in [12]. The size of pore should not be lower than 1 mm because of reflection rather than absorption takes place if pore size is less than 1 mm. The most important feature for determination of the absorption ability of foamed structure is pore connectivity (pore openings) which is estimated to be 0.3 mm. The final output from this study is, that adjusting of manufacturing parameters as infiltration pressure, particle size, wetting angle or surface tension of the alloy can lead to the best absorption ability of the foamed structure.

ALPORAS aluminium foam is widely used for sound-absorption applications. Mechanism of sound energy dissipation in ALPORAS aluminium foams is thoroughly discussed in [11]. Lu et al. [11] consider all possible absorption methods and find out that dissipation is lead mainly via viscous losses mechanism (in the presence of small cracks) according to cracked-array-model. They also described that absorption ability of as-received foam structure do not absorb sound well, therefore it should be improved. Two possible ways for improving (hole drilling and compression) lead to significant increase of absorption ability due to involving cavity resonator mechanism in case of drilling the holes or due to more intensive viscous losses as a result of additional cracks (presented within the structure after compression). However, the combination of these methods offers only a little additional improvement and amount of compression should be adjusted. Small degree of compression results into the little improvement of absorption ability. Contrary, excessive amount results into poor absorption ability.

Effect of density and sample thickness to absorption ability is also discussed in this work. The absorption ability increases with decrease of density due to easiest entering of sound into structure. Optimal thickness of absorber was experimentally estimated to be 10 mm with maximum absorption coefficient 60 %. Lower or higher sample thicknesses do not perform such a good absorption. Applying the air gap behind the sample causes move of SAC to lower frequencies.

Sound absorbing performance of ALULIGHT aluminium foam depends predominantly on the permeability of the structure. As the porosity of aluminium foams is usually closed, it is necessary to open it. Effect of various methods, such as cutting of surface skin, sand blasting, compressing, drilling of various holes was already examined [15]. If the porous structure is opened enough the sound absorption coefficient reaches its maximum within a wider frequency range when compared with simple perforated Al - sheet of the same weight. This range can be shifted by creating an air gap behind the plate using the principle of the Helmholtz resonator. The sound absorption can be

enhanced for wider frequency range by an appropriate design of the absorber, e.g. by combination of several foam plates with an air gap between them.

#### **4. EXPERIMENT**

For better discussing of the results, the experimental part is given according to the production process of metallic foams.

##### ACCESS

Open “cellular” aluminium made via negative pressure infiltration is tested in dependence on various pore size, composition and thickness of absorber. List of samples is presented in

Table 1. Diameter of used granules vary through sample thickness to achieve variable pore size; constant (only one pore size is presented in sample), bimodal (two different pore sizes are separated within sample thickness) and gradient (pore size continually rises). Sample with constant pore size varies from 3-4 mm up to 6-8 mm with step 1-2 mm. The foam is manufactured from different composition (particularly: AlMg, AlSi and Fe) to compare effect of composition to absorption ability; pore size and sample thickness remain constant. Thickness of absorber changes from 10 up to 40 mm with step 10 mm; pore size and composition remain unchanged.

Air gap 0 and 40 mm is applied behind the absorbers of different thickness (10-40 mm). Effect of mineral wool to absorption ability is measured after the air gap is filled by mineral wool of 48 mm thickness. Two pore structures with different flow resistivity are used as reported in



Table 1. The perforated Al sheet is inserted under the granules during manufacturing to ensure reduced open area on the incident side which. The 61 holes with 2 mm diameter were drilled to the Al-sheet. The unknown density is usually between  $0.9 - 1.2 \text{ g.cm}^{-3}$ .

### ALPORAS

Composition of ALPORAS aluminium foam is: 97 % Al + 1.5 % Ca + 1.5 % TiH<sub>2</sub>. Various additional treatments were performed to provide successful improvement of sound-absorption behaviour. The samples for thickening were cut out from block of density  $0.265 \pm 0.014 \text{ g.cm}^{-3}$ ; thickness of samples continuously decreases from 10 mm up to 4 mm with step 1 mm using hack-saw. 61 holes of diameter 2 mm were drilled into sample of 10 mm in order to open the structure – increase of permeability. Other samples were continuously compressed from original thickness (10 and 14 mm) up to 30, 50 and 70 % of original thickness. Finally, the mineral wool is placed behind the sample and rigid wall to observe its influence to absorption ability.

Table 1 List of measured samples.

Foam type	Pore size [mm]	Density [g.cm <sup>-3</sup> ]	Material	Thickness [mm]	Air gap [mm]
ACCESS	4-5	unknown	AlSi	10	0; 40
ACCESS	4-5	unknown	AlSi	20	0; 40
ACCESS	4-5	unknown	AlSi	30	0; 40
ACCESS	4-5	unknown	AlSi	40	0; 40
ACCESS	3-4	unknown	AlSi	20	40
ACCESS	5-6	unknown	AlSi	20	40
ACCESS	6-8	unknown	AlSi	20	40
ACCESS	3-4/8-10	0.966	Al	20	40
ACCESS	3-4/4-6/6-8	0.946	Al	25	0; 48; mineral wool
ACCESS	3-4/4-6/6-8 + Al sheet (61 x 2 mm)	0.946	Al	25	0; 48; mineral wool
ACCESS	3-4/4-8/8-10	0.892	Al	25	48
ACCESS	3-4/4-10/10-12	0.814	Al	25	48
ACCESS	4-6/6-8/8-10	0.895	Al	25	48
ACCESS	4-5	unknown	AlMg	20	40
ACCESS	4-5	unknown	AlSi	20	40
ACCESS	4-5	unknown	Fe	20	40

Table 2 List of measured samples for ALPORAS aluminium foam.

Foam type		Density [g.cm <sup>-3</sup> ]		Thickness [mm]	Air gap [mm]
ALPORAS		0.283		10	0; 20; 40
ALPORAS		0.261		10	48
ALPORAS		0.277		10	48
ALPORAS		0.299		10	48
ALPORAS		0.327		10	48
ALPORAS		0.265 ± 0.014		4; 5; 6; 7; 8; 9; 10; 14	48
ALPORAS	drilled holes: 40 × 2 mm	0.269		10	48
ALPORAS		0.264		10	48
ALPORAS		0.373		10 → 7	48
ALPORAS		0.514		10 → 5	48
ALPORAS		0.844		10 → 3	48
ALPORAS		0.256		14	48
ALPORAS		0.362		14 → 10	48
ALPORAS		0.510		14 → 7	48
ALPORAS		0.704		14 → 5	48
ALPORAS	compressed from 10 up to 5 mm	0.470		10	0; 48; mineral wool
ALPORAS	EMS insertion	0.371		7	48
ALPORAS	EMS insertion	0.334		8	48

### ALULIGHT

Composition of ALULOGH aluminium foam is: AlSi12 alloy or AlMg1Si0.6 alloy with 0.4 % TiH<sub>2</sub>. Various additional treatments were performed to provide successful improvement of sound-absorption behaviour. Various number of holes with various diameter were drilled into sample, the surface skin was removed by various methods to open the structure – increase of permeability. Finally, the mineral wool is placed behind the sample and rigid wall to observe its influence to absorption ability.

Table 3 List of measured samples for ALULIGHT aluminium foam.

Foam type		Density [g.cm <sup>-3</sup> ]		Thickness [mm]	Air gap [mm]
ALULIGHT	drilled holes 0; 19; 61; 160; 250; 382 x 1 mm	0.450		8.9	40
ALULIGHT	drilled holes 61 x 1; 1.5; 2; 2.5; 3 mm	0.450		8.9	40
ALULIGHT	drilled holes 61 x 2 mm	0.450		8.9	0; 5; 10; 20; 30; 40
ALULIGHT	drilled holes 61 x 2 mm; different dept of holes: 0.25; 0.5; 0.75; 1	0.383		15	0
ALULIGHT	milled out the surface skin	0.550		5	40
ALULIGHT	sand-blasting	0.318		15	0; 48
ALULIGHT	sand-blasting + drilling the holes; 61 x 2mm	0.318		15	0; 48; ; mineral wool
ALULIGHT	drilled holes; 61 x 2 mm	0.413		8.9	0; 48; ; mineral wool

Test method:

Ability of material to absorb sound energy is described by sound absorption coefficient. The absorbed fraction of the sound energy of a plane sound-wave after incident on a material is term as sound-absorption coefficient [5], [11]. There are two possible ways widely used for measurement of sound absorption coefficient: plane-wave impedance method or reverberation room method. In our study, the plane-wave impedance tube method is used rather than reverberation room due to quicker, cheaper and easier way for obtaining the sound absorption coefficient. In case of reverberation room, the large amount of absorption material is needed (between 14.5 and 17.4 m<sup>2</sup>) and in contrast; it is only 0.153 m<sup>2</sup> in case of impedance tube method. It means that preparation and measurement process is less time consumption for impedance tube method. Test was carried out according to ISO EN 10 534 [16] and schematic description is presented in Fig. 6. The sound is generated by load-speaker at one end of the tube and travels towards the sample which is placed at the other end and is sealed to avoid the additional losses of the sound energy. The principle of measurement is to obtain pressure drop by moving the probe. Absorption coefficient is then calculated from equation

$$\alpha = 1 - \left( \frac{p_{\max.}/p_{\min.} - 1}{p_{\max.}/p_{\min.} + 1} \right)^2 \quad (3)$$

where  $p_{\max.}$  is maximal and  $p_{\min.}$  is minimal pressure measured by moving probe.

Absorption coefficient can reach values from 0 up to 1.00 in frequency range between 100 and 2000 Hz if sample diameter is 99 mm. The smaller samples (20 mm in diameter) ought to be used to

obtain absorption coefficient for frequency range: 2000 Hz up to 6300 Hz. The absorption coefficient can reach values even higher than 1.00 when measured in reverberation room due to contribution of sample edge absorption effect. This effect is not included in case of impedance tube. The certain amount of sound energy is absorbed just by edge effect. In reverberation room, there are waves spreading under various angles (reverberant sound field) and in impedance tube, only absorption coefficient of plane wave is measured. The absorption coefficient obtained at lower frequencies is higher in reverberation room and do not significantly vary in comparison with impedance method at higher frequencies.

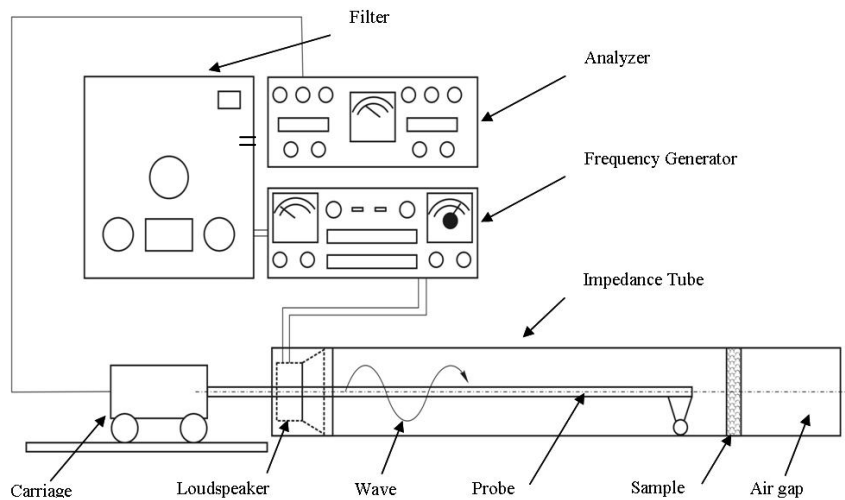


Fig. 6. Schematic description of sound-absorption coefficient measurement via impedance tube method.

## 5. Experimental results and discussion

### Material composition

It is generally accepted, that the aluminium foam structure is stochastic with difficult reproducibility. It is very difficult therefore to investigate the effect of material composition on sound absorption of foams. However, in the case of ACCESS foams the structure of cellular material is homogeneous and reproducible, thus enabling such investigation. As indicates Fig. 7 the brittle aluminium alloy AlSi possesses at bit better sound absorption properties as wrought AlMg alloy at the same porosity. The importance of structure opening is evident when we compare the results for aluminium alloys with the iron foams sound absorption. It can be concluded that the *sound absorption properties of foam material itself are less important as foam porosity and the degree of structure opening.*

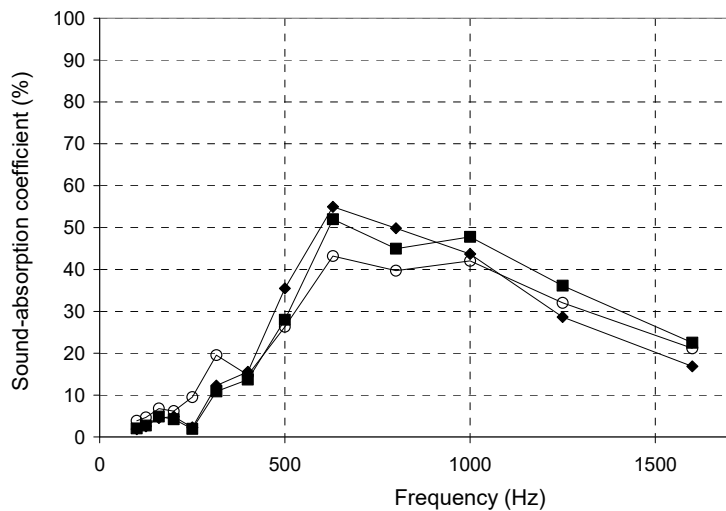


Fig. 7. Effect of different alloy composition on absorption ability of the samples;  
 Size of pores: 4-5 mm; thickness: 20 mm, air gap: 40 mm; porosity: constant.

#### Methods for opening the structure

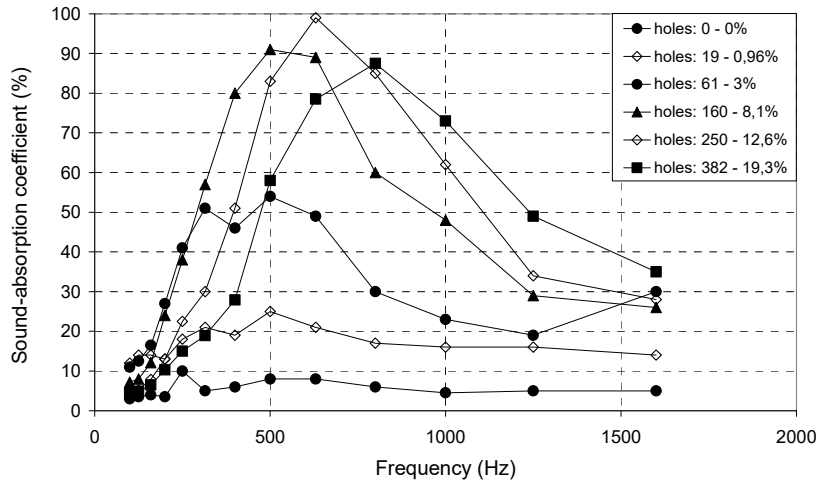
There is a lot of ways how to open the structure of foam. Primary one is a method of preparation leading to either open or closed porosity. Then it is the degree of foam porosity, thickness of foam sheet used for sound absorption, foam structure, air gap behind the foam sheet. Moreover, the structure can be opened by various surface machining, drilling or punching of holes, sandblasting, electro spark machining, sheet deformation in compression or rolling. Finally, the air gap behind the foam sheet can be filled with mineral wool to improve the sound absorption.

For this reason the results concerning opening of the foam structure will be further presented separately according to cellular metal preparation method.

#### ALULIGHT

Presence of surface skin blocks the sound wave to enter into foam cellular structure. The sound energy is therefore reflected back to surrounding without any absorption [5], for that reason it is always necessary to open the surface to use metallic foams with surface skin as sound absorber. The easiest way for opening the structure is drilling the holes which will lead to absorption via cavity resonator mechanism. Contribution of viscous losses in this case is negligible due to smooth skin surface. *As number of holes of constant diameter increase*, the structure become more permeable which results into significant improvement of absorption ability due to more sound energy engaged in absorption mechanism (Fig. 8a). The best improvement of sound absorption ability is observed for structure with 250 holes which means that 12.6% of structure is opened. If openness of the structure approximates value 12.6%, absorption ability increases and, reversible, if 12.6% is overcome, the absorption ability starts to worsen. On the Fig. 8b, there is presented *effect of diameter of holes* to absorption ability if *number of holes is constant*. As in previous case, the absorption ability become improved as hole diameter increases due to increased permeability of the structure, until 12.3% of structure is opened. Afterwards, the absorption ability starts to decrease. It must be noted, that the samples are not placed onto rigid wall due to effect of cavity resonator mechanism.

a



b

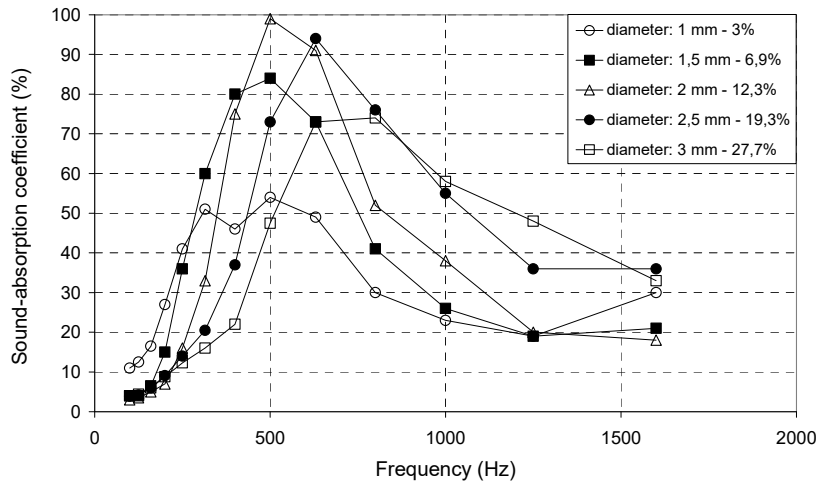


Fig. 8. Effect of number of holes (a) and hole diameter (b) on the sound absorption ability; diameter of holes in case of (a) is 1 mm and number of holes in case of (b) is 61, air gap behind the sample is 40 mm; density:  $0.450 \text{ g.cm}^{-3}$ ; sample thickness: 8.9 mm. Percents in legend mean the amount of structure opened.

As can be seen for given pore size, foam thickness and density ( $450 \text{ g.cm}^{-3}$ ) the optimal opening of foam surface is only 10 – 14 % of the whole foam surface regardless it is achieved by increasing number of holes at constant diameter of holes or by increasing of diameter of holes at constant hole number. Of course there is a different resonant frequency (larger resonator volume for variable diameter of holes at constant number of holes gives lower resonant frequency) and bandwidth of absorption peak for both approaches. It can be concluded from abovementioned, that there is an optimal permeability of the structure which provides maximal improvement of the absorption ability at given foam pore size and density.

Effect of various air gaps behind the sample is well known for foams and we present it in Fig. 9. The absorbed frequency range is moved to lower frequencies as an air gap behind the sample increases due to higher kinetic energy for frequencies with low wavelength ( $\lambda/4$ ). The energy dissipation is more intensive if sound wave enters the structure just at quarter of wavelength – lower frequency means higher wavelength and thicker absorber due to  $\lambda/4$ .

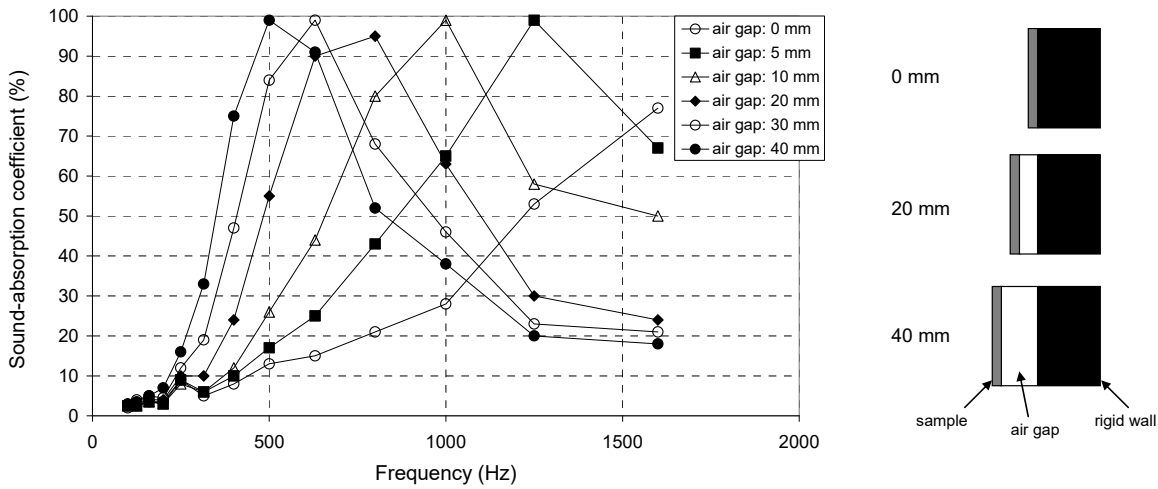


Fig. 9. Influence of air gap behind the sample for sample with 61 holes of 2 mm diameter; sample thickness: 8.9 mm; density: 0.450 g.cm<sup>-3</sup>.

It is evident that in the case of closed cell aluminium foams the foam itself behaves only as aesthetic cover sheet which after proper opening (drilling, rolling, punching) enables sound to enter into air gap behind the foam panel, where it is absorbed. However, due to higher thickness (at least 5 mm and more) in comparison with simple aluminium sheet and foam cellular structure the situation is more complex.

To investigate the effect of foam structure itself on the sound absorption, the holes of different constant depth were drilled into the same foam sample subsequently. The foam sample was chosen thicker in this case to better investigate the studied effect. Fig. 10 shows an effect of hole depth on absorption ability of foam structure. In this case the structure opening continuously increases so far until the structure is fully perforated (samples are placed directly onto rigid wall to study mostly the sound absorption of foam). As depth of holes and cavity volume increase, the absorption ability becomes improved. If we assume, that the holes present the volume and impedance tube acts as a cavity the resonant frequency ought to shift to lower frequency with increasing volume of cavity inside the foam. The opposite is true. It confirms, that there is other absorption mechanism which can provide significant improvement of absorption ability of foam itself – viscous losses mechanism (dissipation of the sound energy within the structure – cracks, bendings, etc.).



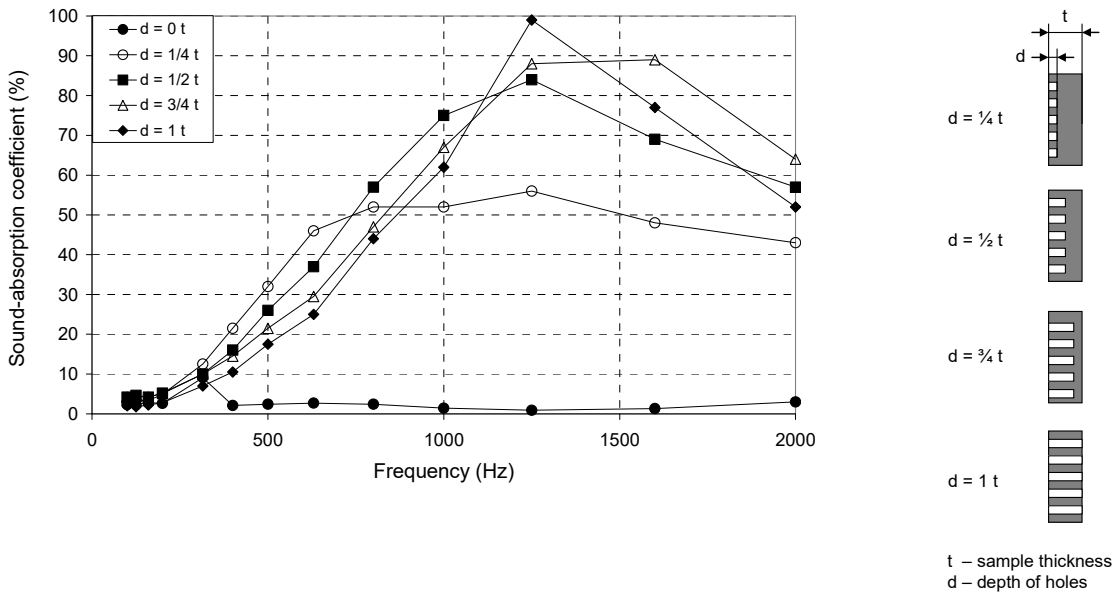


Fig. 10. Influence of different dept of holes on the sound-absorption ability of foam; number of holes:  $61 \times 2$  mm; thickness: 15 mm; density:  $0.383 \text{ g.cm}^{-3}$ ; no air gap is applied behind

If we compare the sample in Fig. 10 where the holes are drilled through the thickness, with those in Fig. 8b (both  $61 \times 2$  mm); one can see that almost double increase of absorber thickness is needed to provide absorption ability at lower frequencies if absorber is placed directly onto rigid wall.

From technological point of view it is necessary to compare how various methods of removing of the foam surface skin and opening of foam structure (Fig. 11) affects the sound absorption abilities of PM aluminium foam.

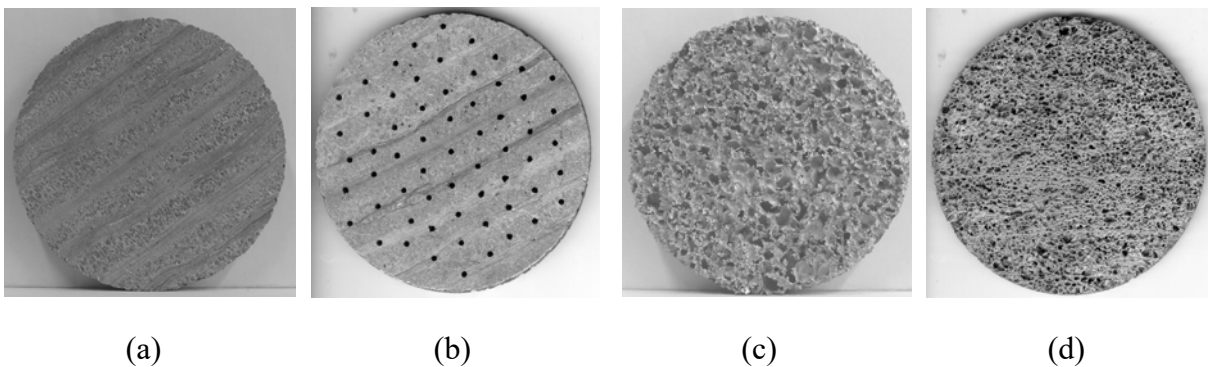


Fig. 11. Structure of foam samples after different surface treatments; (a) not-open; (b) after drilling the holes into structure; (c) after milling out the surface skin; (d) after sand-blasting.

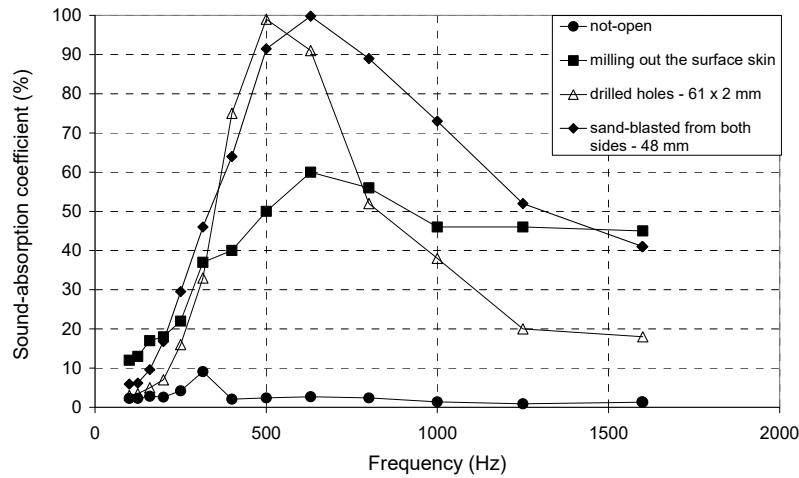


Fig. 12. Effect of various treatment of the structure on the sound absorption ability; density:  $0.550 \text{ g.cm}^{-3}$ ; thickness: 5 mm; air gap: 40 mm.

Effect of various structural treatments on the absorption ability is shown in Fig. 12. The improvement of absorption ability in case of milling out the surface skin (Fig. 9c) is significant in comparison with non-treated sample. Sample with drilled holes perform better. It suggests that penetration of sound wave is not sufficient and part of its energy is reflected to surrounding without absorption. Result is improved but with insufficient absorption ability. It is evident that this approach can be used successfully only for small thickness of foam sheets.

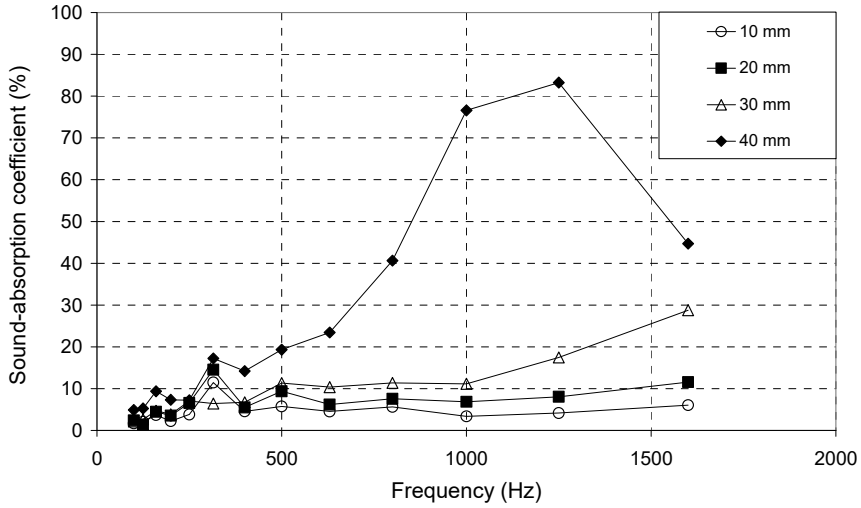
Different situation occurs if sample is sand-blasted (Fig. 9d) - very small sand particles are blasted onto surface of aluminium foam and remove it by tearing. As a result of high pressure and very small particles, the structure is not only open (without surface skin) but, other pore faces under the surface skin are also broken (tearing). This is not observed for milling because milling remove only surface skin without any other structure modification. Result is deeper penetration of the sound wave to the structure thus more intensive viscous losses which lead to improvement of absorption ability presented in Fig. 12. Also in this case the thickness of used foam sheet is limited from upper side.

### ACCESS

Absorption ability of open cellular material placed directly to rigid wall is lead mainly via viscous losses mechanism which depends on flow resistance of the pore structure [11, 12]. Guiping et. al [14] in their study suggest that sound energy is absorbed by strands vibration as sound enter into structure. It will be considered in discussion for this type of metallic foam that the pore structure is too stiff to vibrate under sound pressure and absorption ability is lead predominantly by viscous losses mechanism as reported in [11, 12]. Increase of flow resistance can be achieved by adjusting the sample thickness or by the decrease of the pore size. Flow resistance of the sample increases with increase of its thickness due to more intensive interaction between the sound wave and structure is shown in Fig. 13. In case of adjusting the size of pores; smaller pore size leads to more intensive energy dissipation through the same volume due to more pores per unit area, which increases amount of interaction between sound wave and pore structure. The result is more intensive energy dissipation as demonstrated in Fig. 14. The absorption ability at low frequencies is again improved when an air gap behind the absorber is applied (compare Fig. 13a with 0 mm air-

gap and Fig. 13b, where 40 mm air-gap is left behind the sample). The reader ought to keep in mind the density of typical ACCESS aluminium foam around  $1\text{g.cm}^{-3}$ .

a



b

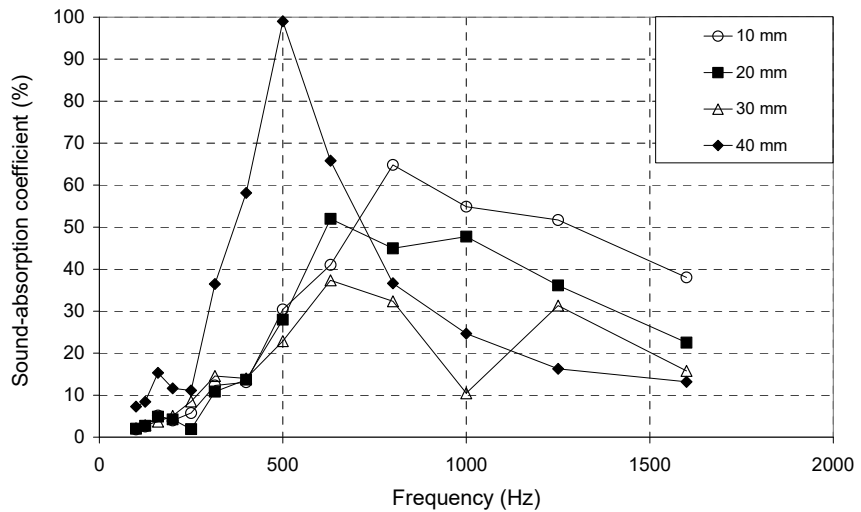


Fig. 13. Effect of the sample thickness to sound-absorption ability of the ACCESS; size of pores: 4-5 mm. (a) air gap is 0 mm and (b) 40 mm air gap is applied behind the sample.

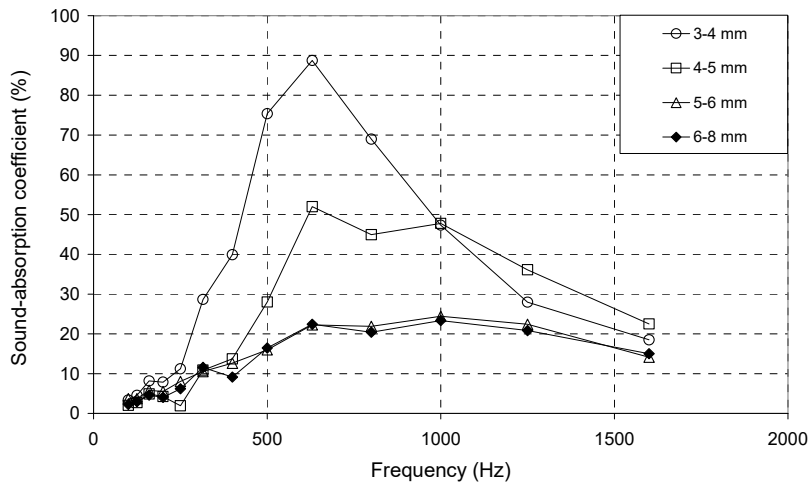


Fig. 14. Effect of different pore size, sample thickness is 20 mm and air gap 40 mm.

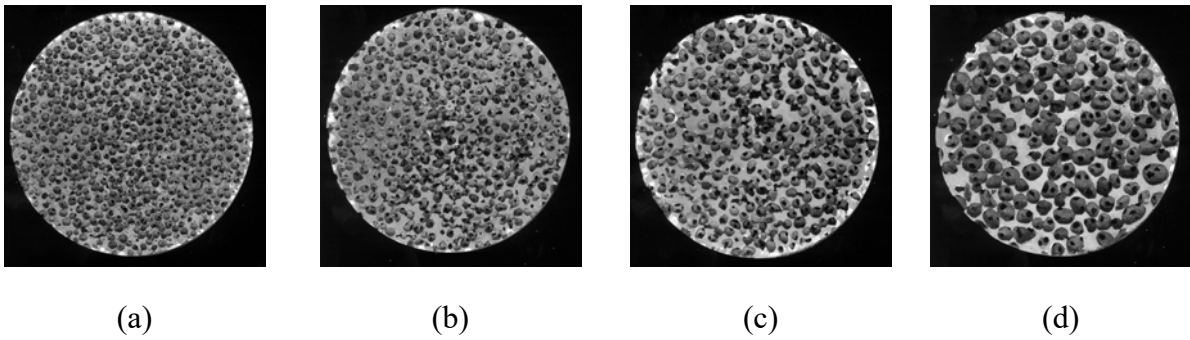


Fig. 15. Different sizes of pores for open cellular material; (a) 3-4 mm; (b) 4-5 mm; (c) 5-6 mm; (d) 6-8 mm.

The manufacturing method allows simple change of the pore size through thickness thus enabling the production of gradient or bimodal structures (Fig. 15). Effect of gradient pore structure on the absorption ability is presented in Fig. 16. Absorption ability is not good enough in comparison with constant pore structure of same pore size on incident side due to limitation of viscous mechanism within the part of structure with bigger pores. The most effective between the gradient pore structures is sample 3-4/4-6/6-8 mm, which contains the smallest pore size through sample thickness.

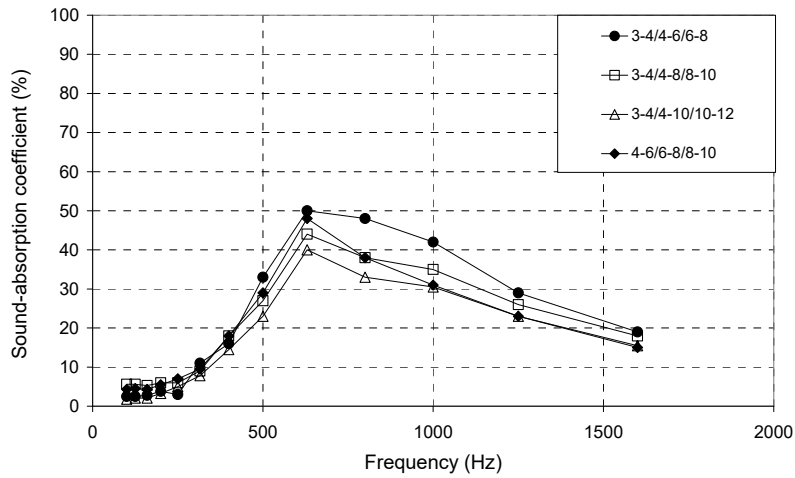


Fig. 16. Effect of different modification of the pore size within the gradient pore structure; sample thickness: 25 mm; air gap: 48 mm.

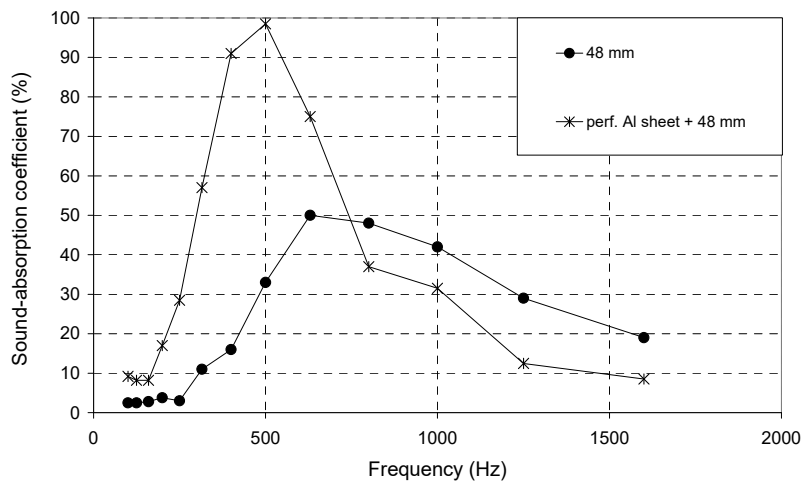


Fig. 17. Comparison of absorption ability for gradient sample 3-4/4-6/6-8 after addition of perforated sheet ( $61 \times 2$  mm) in front of the sample; sample thickness is 25 mm, air gap is 48 mm.

The significant improvement of absorption ability for gradient structure (3-4/4-6/6-8) can be achieved if perforated aluminium sheet ( $61 \times 2$  mm) is added into structure during manufacturing, see Fig. 17. On the other hand a usual approach in architecture is to fill air gap behind cover sheet with mineral wool to improve the sound absorption. It is evident, that the replacing of the air gap between foam and rigid wall by mineral wool lead to significant improvement of absorption ability as presented in Fig. 18. The reason is simple; sound energy which is not reflected or absorbed by the foam transit across the structure and is absorbed by the mineral wool. Mineral wool dissipates sound energy via viscous losses mechanism more intensive than aluminium foam due to its flexible structure.

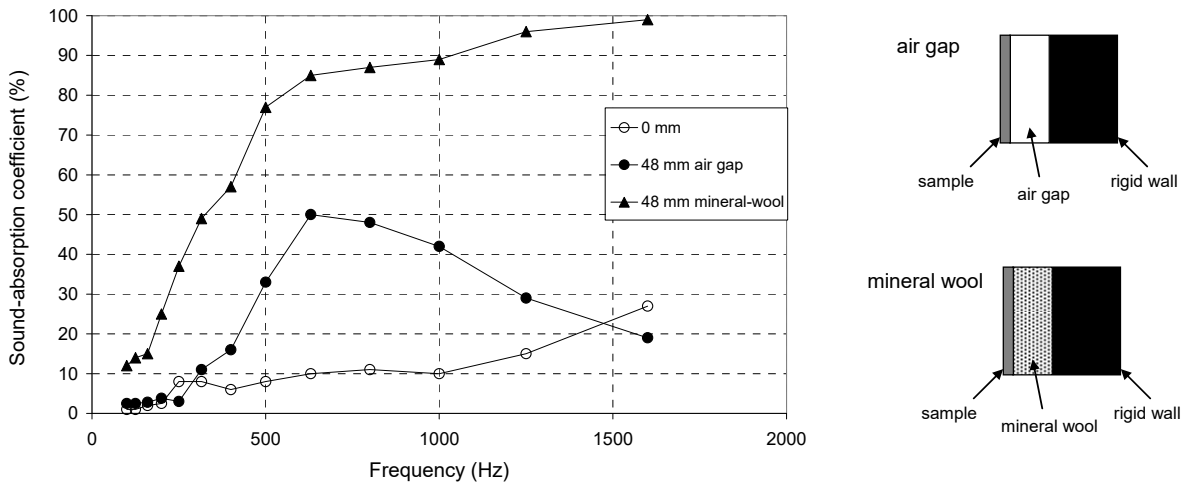


Fig. 18. Effect of different filling behind the sample; air gap is filled by mineral-wool; thickness: 25 mm; pore size: 3-4/4-6/6-8 mm.

### ALPORAS

The absorption mechanism inside ALPORAS foam is lead mainly via viscous losses mechanism [12]. But this mechanism is not sufficient enough to provide absorption of sound as it happens if sound wave interacts with typical acoustic absorber e.g. mineral wool.

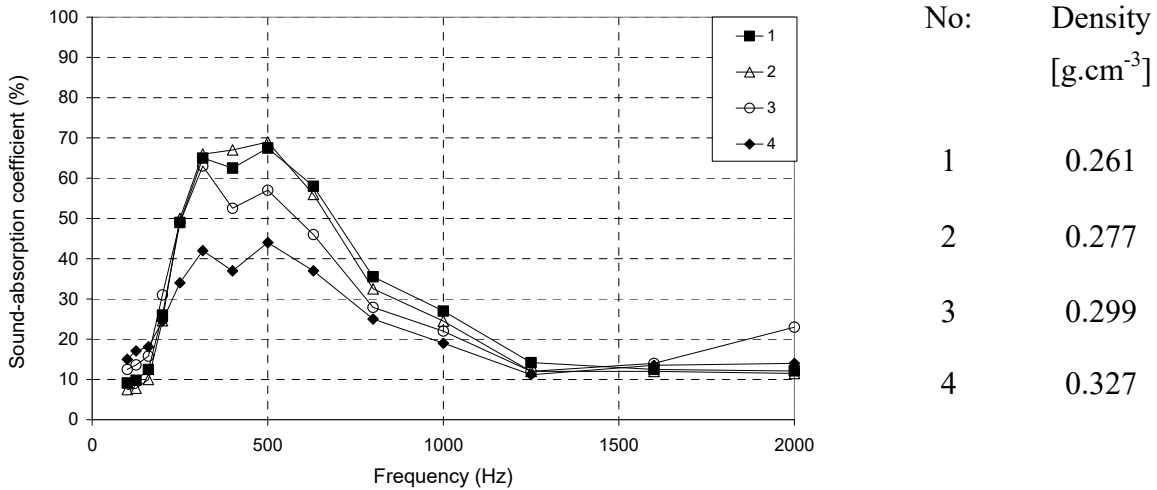


Fig. 19. Effect of different density to sound-absorption ability of ALPORAS aluminium foam; sample thickness: 10 mm; air gap: 48 mm.

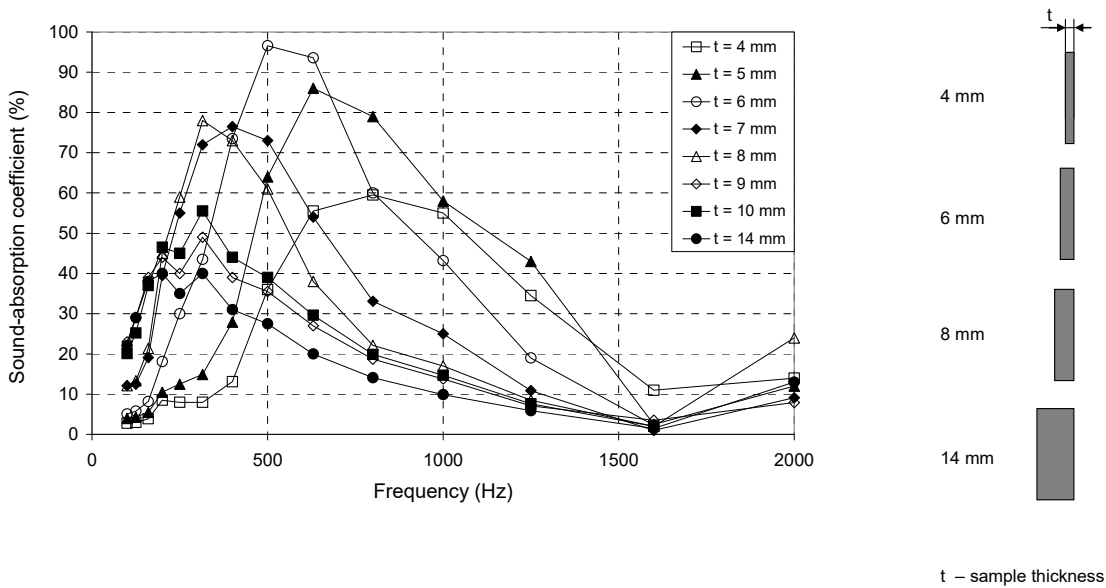


Fig. 20. Effect of thickening to absorption ability; samples were cut from block of density:  $0.265 \pm 0.014 \text{ g.cm}^{-3}$ ; air gap: 48 mm.

Effect of material density and material thickness to absorption ability for ALPORAS aluminium foam is presented in Fig. 19 and in Fig. 20. The absorption ability is improved as density decreases (Fig. 19) and with decreasing of the sample thickness (Fig. 20). Viscous losses absorption mechanism is not sufficient enough to provide good dissipation of sound energy if sample is thicker than 9 mm. Permeability of such structure is lead only via small cracks and holes within the pore faces (Fig. 21 a-b) and macroscopically, the structure is not permeable (Fig. 21a). However, as sample thickness continuously decreases, structure become macroscopically permeable (Fig. 21b) and absorption ability in air gap behind is improved. The absorption coefficient achieves 97% at 500 Hz and 630 Hz if sample thickness is 6 mm. Reason is that cavity resonator mechanism is involved as sample thickness decreases. This mechanism is characteristic by high absorption coefficient within narrow frequency range [17] which is also observed in case of 6 mm sample thickness presented in Fig. 22. Other decrease of sample thickness worsens absorption ability due to even more increasing surface opening and also foam permeability (see opacity of such foam in Fig. 21c).

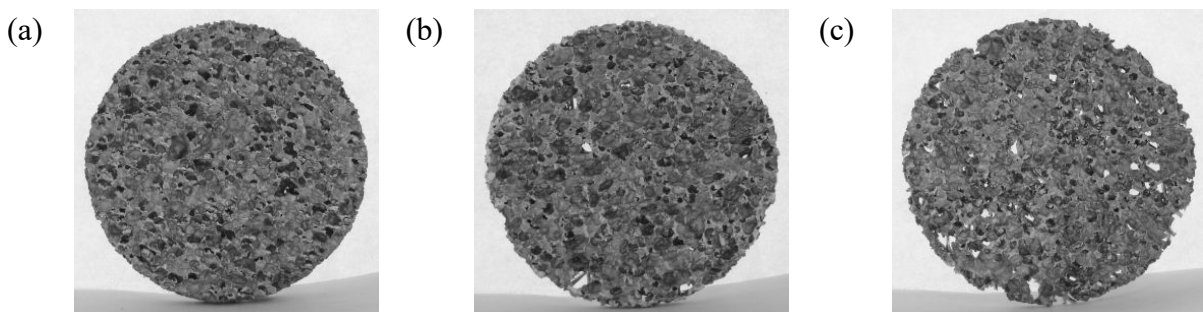


Fig. 21. Differences within the pore structure of ALPORAS aluminium foam in dependence on sample thickness; (a) 10 mm – low permeability, (b) 6 mm – sufficient permeability and (c) 4 mm – over-permeable structure.

From abovementioned, the absorption ability of ALPORAS aluminium foam can be successfully and significantly improved by making the structure more permeable (by thickening or by drilling the holes) which involve additional cavity resonator absorption mechanism. But, the absorbed frequency range is narrow and should be widened. One possible way to avoid this is to compress the sample which adds additional cracks into structure thus possibly increasing of viscous losses absorption mechanism.

Effect of progressive compression on the absorption ability for different original sample thicknesses (10 and 14 mm) is presented in Fig. 22 and Fig. 23. Even 30% of compression provides improvement of absorption ability. Progressive compression (50 % or 70 %) results into minimally doubled and significantly widened absorption range in comparison with a non-compressed structure for both thicknesses. The reason is shown in Fig. 24a – d; small holes (openings) within pore faces which lead the absorption mechanism via viscous losses change to cracks with creation of additional small or large cracks as a result of face bending during the compression. These structural features improve dissipation of the sound energy which is in agreement with observation of Lu et. al [11].

It can be stated that the absorption ability is significantly improved after 30% and 50% compression and the effect of additional compression does not provide any additional improvement. Reason is explained by Lu et. al. [11]: If compression proportion is low, only a few cell faces break, rendering little enhancement in sound absorption. On the other hand, if compression proportion is too high, the cells crush and shrink in size to block the air path – resulting foam have poor acoustic performance.

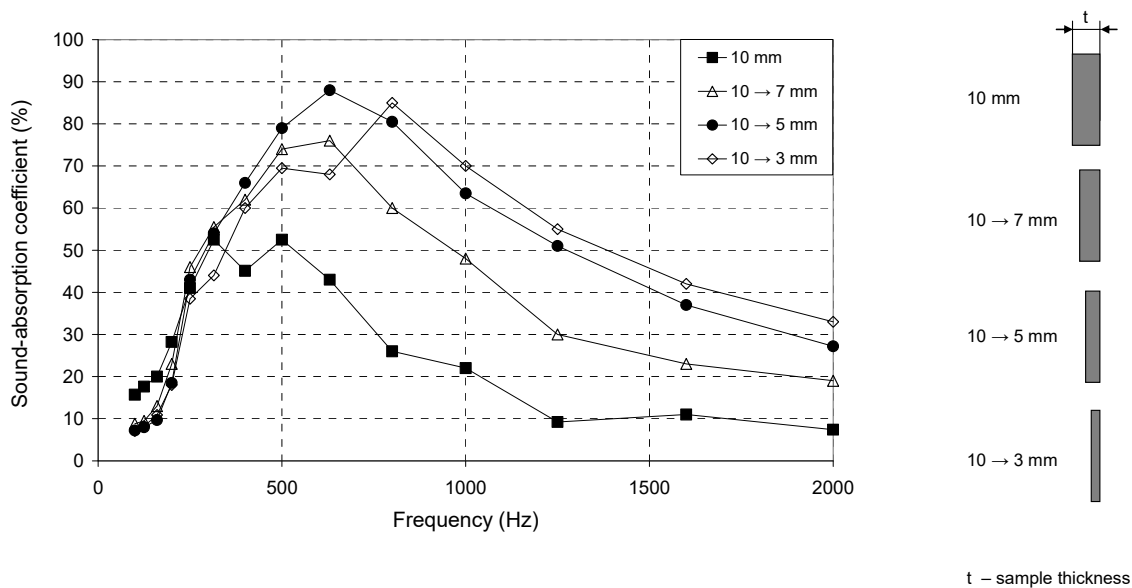


Fig. 22. Effect of gradual compression to different final sample thickness, sample thickness: 10, 7, 5, 3 mm, air gap: 48 mm; number after arrow presents the thickness of sample after compression; densities: 10 mm = 0.264 g.cm<sup>-3</sup>; 10 → 7 mm = 0.373 g.cm<sup>-3</sup>; 10 → 5 mm = 0.514 g.cm<sup>-3</sup>; 10 → 3 mm = 0.844 g.cm<sup>-3</sup>.

It is evident, that besides optimal compression there is also optimal thickness of foam before compression at given porosity. Too thick samples cannot be successfully surface opened and their permeability cannot be further improved as their structure after compression prevents the air to percolate via foam thickness.



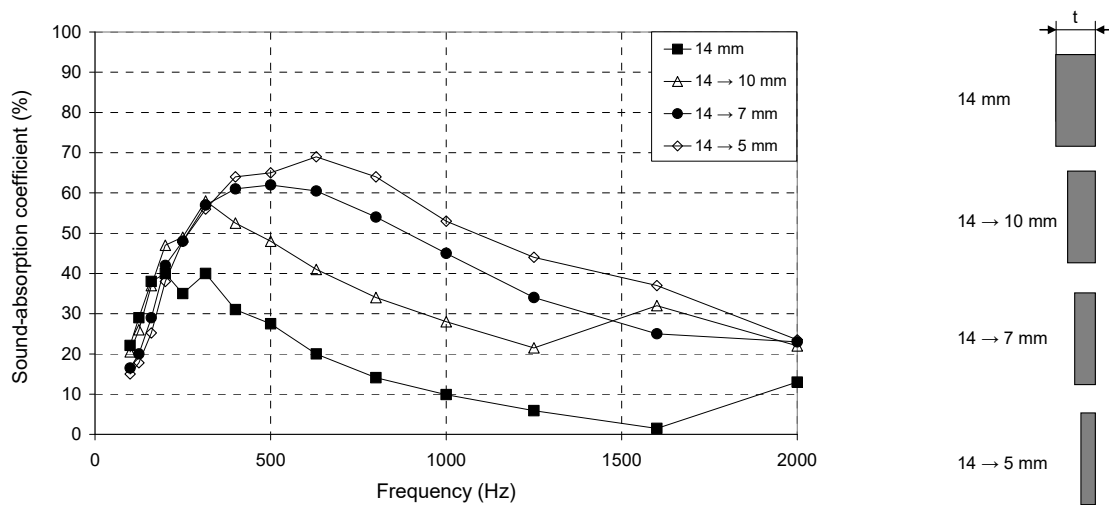


Fig. 23. Effect of gradual compression to different final sample thickness; sample thickness: 14, 10, 7, 5 mm, air gap: 48 mm, number after arrow presents the thickness of sample after compression, densities: 14 mm =  $0.256 \text{ g.cm}^{-3}$ ; 14 → 10 mm =  $0.362 \text{ g.cm}^{-3}$ ; 14 → 10 mm =  $0.510 \text{ g.cm}^{-3}$ ; 14 → 5 mm =  $0.704 \text{ g.cm}^{-3}$ .

There is no absorption peak in case of compression, but frequency range absorbed above 60% of absorption coefficient is almost doubled in comparison with that observed for sample thickening. It suggests that both additional treatments (compression or permeability increase) provide good and typical improvement of absorption ability via viscous losses mechanism or via cavity resonator.

## 6. Conclusions

The sound absorption properties of foams depend predominantly on the foam porosity and opening of its structure and only after that on the properties of foam cell wall material. For this reason we will discuss the results with respect to method of aluminium foam preparation.

### ALULIGHT

The ALULIGHT aluminium foam is covered by continuous surface skin which does not allow the sound to enter into the structure and to be successfully dissipated. Therefore, there is a need to modify the structure to open it for good sound absorption ability. Then two absorption mechanisms can take place: absorption via cavity resonator mechanism and absorption via viscous losses mechanism. Absorption via cavity resonator mechanism is the most significant and is usually improved by drilling the holes into the foam. However, in this case an absorbed frequency range is narrow and should be improved. This can be done by removing the dense surface skin which allows the sound to enter the structure and be successfully dissipated. If surface skin is only milled out, the absorption ability is improved in comparison with a non-treated sample but not as significant as in case of drilling the holes. Sand blasting of the structure makes it even more permeable which result into very good absorption ability. Finally, it is recommended to use air gap behind and even fill it with good sound absorbers as mineral wool, etc.

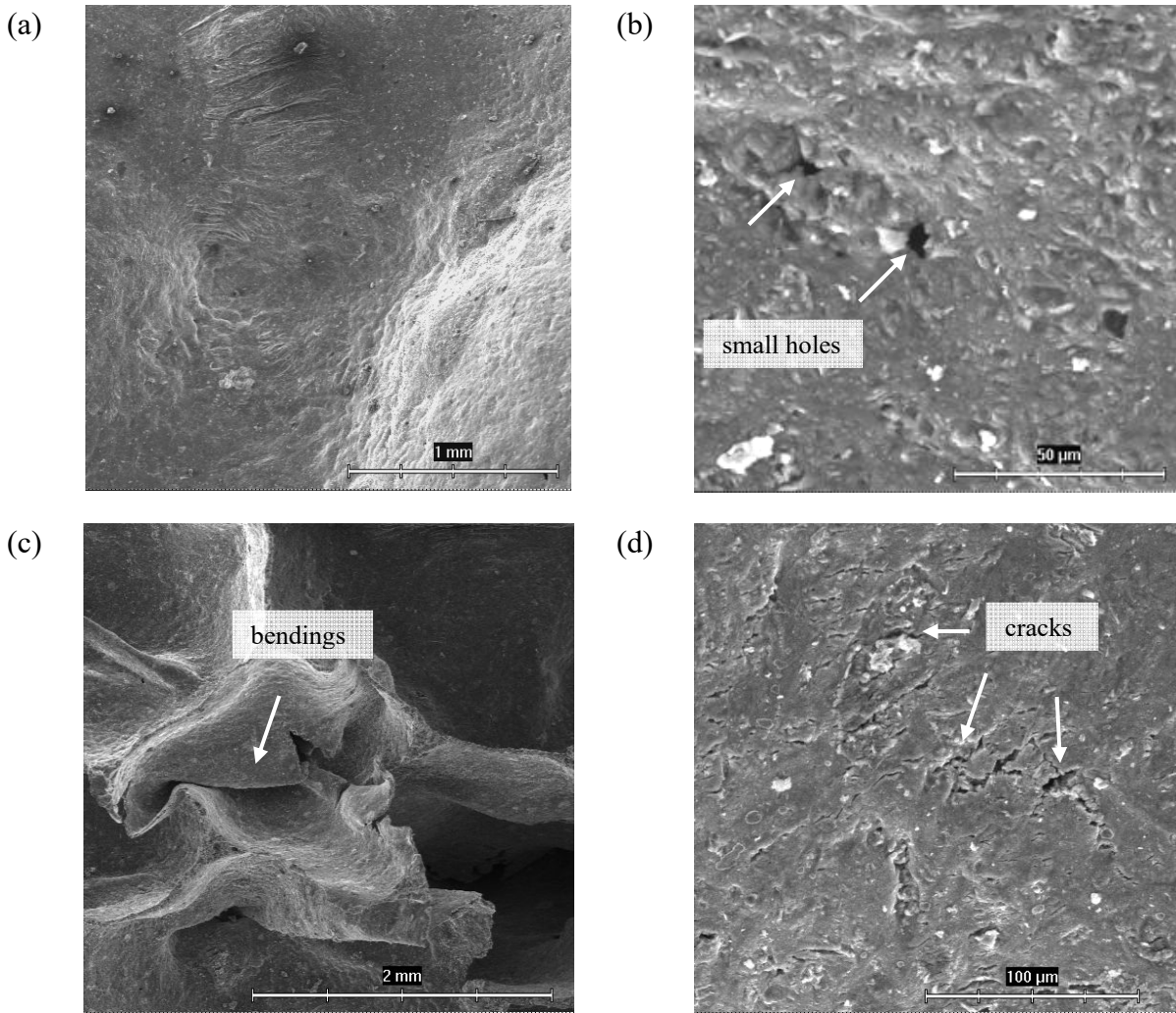


Fig. 24. Evolution of macro (left column) and microstructure (right column) during the compression; (a) and (b) presents the structure before and (c) and (d) after compression from 10 up to 5 mm.

### ACCESS

The absorption ability of ACCESS aluminium foam can be adjusted to absorb required frequency range (from 100 Hz up to 2000 Hz) by increasing of flow resistance of the structure together with introducing the air gap behind the absorber. Increase of flow resistance can be done by gradient increase of pore size. Even high increase of sound absorption can be achieved if perforated Al-sheet is inserted at incident side of the absorber during the preparation of foam. Size of holes within the perforated Al-sheet should be lower than size of pores within the foam structure. Applying the air gap between foam and rigid wall moves the absorbed frequency range to lower frequencies due to high kinetic energy at  $\lambda/4$ . Absorbed frequency range can be widened by replacing the air gap behind the sample and rigid wall by mineral wool. This allows absorbing high frequencies which depends on the flow resistance of the structure.

### ALPORAS

Air gap applied between sample and rigid wall is needed to increase absorption ability of ALPORAS aluminium foam at low frequencies. However, the sound-energy dissipation is not

sufficient enough and can be improved by additional treatment via decreasing of the sample thickness by cutting or by compression. This decreasing of thickness provides successful improvement of sound absorption by involving cavity resonator absorption mechanism. On the other hand, progressive compression results into creation of additional cracks which improve viscous losses absorption mechanism.

## Acknowledgements

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## References

- [1] Beranek, L.L.: Noise Reduction. McGraw-Hill Book Company, Inc., New York, 1960.
- [2] Gibson, L.J. – Ashby, M.F.: Cellular solids. Cambridge University Press, 1997.
- [3] Ashby, M.F. – Evans, A.G. – Gibson, L.J. – Hutchinson, J.W. – Wadley, H.N.G.: Metal Foam: A Design Guide, 2000, Butterworth-Heinemann.
- [4] Banhart, J.: Manufacture, characterization and application of cellular metals and metal foams. *Progress in Material Science*, 46, 2001, p. 559–632.
- [5] Kováčik, J. – Šimančík, F.: Electrical, thermal and acoustic properties of metallic foams. In: *Handbook of Cellular Metals. Production, Processing, Applications*. 2002, Wiley-WCH.
- [6] T. Miyoshi, M. Itoh, S. Akiyama, A. Kitahara: ALPORAS aluminum foam: Production process, properties, and applications *Advanced Engineering Materials*, 2 (2000), pp. 179-183 and Shinko Wire Co, Japan, 1995 – 2010 data sheets and presentations.
- [7] Wei Jin, Jiaan Liu, Zhili Wang, Yonghua Wang, Zheng Cao, Yaohui Liu, Xianyong Zhu., Sound Absorption Characteristics of Aluminum Foams Treated by Plasma Electrolytic Oxidation. *Materials* 8:11, 2015, 7511-7518.
- [8] Yunjie Li, Zhendong Li, Fusheng Han, Air Flow Resistance and Sound Absorption Behavior of Open-celled Aluminum Foams with Spherical Cells, *Procedia Materials Science*, Volume 4, 2014, Pages 187-190, ISSN 2211-8128.
- [9] Kováčik, J., Orovčík, E., Jerz, J., High-temperature compression of closed cell aluminium foams. In *Kovove Mater.*, 2016, Vol 54, No. 6, pp. 429-440. ISSN 0023-432X.
- [10] Han, F. – Seiffert, G. – Zhao, Y. – Gibbs, B.: Acoustic absorption behaviour of an open-celled aluminium foam, *Journal of physics D: Applied Physics* 36, (2003) 294-302.
- [11] Lu, T. J. – Hess, A. – Ashby, M. F.: Sound absorption in metallic foams, *Journal of applied Physics* 85, (1999) 7528.
- [12] T.J. Lu, F. Chen, D.P. He: Sound absorption of cellular metals with semi open cells, *Journal of Acoustic Society of America*, 108 (2000), pp. 1697-1709.
- [13] Nosko, M., Reproducibility of aluminium foam properties. PhD. Dissertation. IMMM SAS, Bratislava, 2005.
- [14] Guiping, G. – Deping, H. – Guangji, S.: Underwater property of porous aluminum, *Colloids and surfaces A*, (2001), 191-194.
- [15] Kováčik, J. et al.: In: *Metal foams and porous metal structures*, Ed. by J. Banhart, M.F. Ashby, N. A. Fleck, Verlag MIT publishing, Bremen 1999, p. 405.
- [16] EN ISO 10534 – 1, Acoustics – Determination of sound absorption coefficient and impedance in impedance tubes -- Part 1: Method using standing wave ratio, June 2001.
- [17] C. Perrot, F. Chevillotte, M.T. Hoang, G. Bonnet, F.X. Becot, L. Gautron, A. Duval: Microstructure, transport, and acoustic properties of open-cell foam samples: Experiments and three-dimensional numerical simulations, *Journal of Applied Physics*, 111 (2012), p. 014911.