# ALUMINIUM FOAM – A NEW LIGHT-WEIGHT STRUCTURAL MATERIAL

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Aluminium foam is an isotropic highly porous metallic material with a cellular structure. The essentially spherical and closed pores occupy more than 70% of the total volume. Mechanical and physical properties depend strongly on the density which lies typically in the range of 0.4–1.2 g.cm$^{-3}$. Aluminium foam prepared by a powder metallurgical method is very efficient in sound absorption, electromagnetic shielding, impact energy absorption, and vibration damping. It is non-flammable and form-stable at elevated temperature. Aluminium foam is recyclable and thus environmentally friendly. For future industrial applications it offers the combination of apparently concurrent properties in one homogeneous material, thus saving material, energy, and environment. The aim of this paper is to describe selected mechanical and physical properties of this remarkable metallic material and to give an outline for its potential utilisation.

# PENOVÝ HLINÍK – NOVÝ ĽAHKÝ KONŠTRUKČNÝ MATERIÁL

Penový hliník je izotropný kovový materiál s celulárnou štruktúrou. Čiastočne uzatvorené póry sférického tvaru tvoria viac ako 70% jeho celkového objemu. Penový hliník pripravený technológiami práškovej metalurgie veľmi efektívne pohlcuje zvuk, nárazovú energiu, odtieňuje elektromagnetické vlnenie a dobre tlmí vibrácie. Jeho mechanické a fyzikálne vlastnosti významne závisia od hustoty, ktorá zvyčajne dosahuje hodnoty od 0,4 do 1,2 g.cm$^{-3}$. Penový hliník je tvarovo stály aj pri vyšších teplotách, je recyklovateľný a ekologicky nezávadný. Pre budúce priemyselné použitie ponúka kombináciu zdanlivo protichodných vlastností v jedinom homogénnom materiáli, čím šetrí suroviny, energiu i životné prostredie. Cieľom článku je stručne informovať o niektorých mechanických a fyzikálnych vlastnostiach tohto zaujímavého kovového materiálu, ktoré najviac predurčujú jeho budúce praktické využitie.

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## 1. Introduction

The evolution of the mankind is going hand in hand with a request for new constructional and tool materials. Until recently, the principal evolutionary forces were those relating to improved performance and functionality. Although the polymers, ceramics, or composites have already been employed in various industrial applications the demand for stronger, stiffer and lighter materials is still growing. However, the production, disposal, and use of materials in products have environmental impacts throughout the whole product life cycle, and this fact cannot be longer ignored.

The strong and stiff materials can be found also in the nature but they usually do not induce any recycling and pollution problems. Therefore they can be a very good guide for the prospective development of new materials. The difference between strong natural and artificial materials has been very well characterised by Ashby [1]: "When modern man builds large load-bearing structures, he uses dense solids: steel, concrete, glass. When Nature does the same, she generally uses cellular materials: wood, bone, coral." Really, natural materials are strong enough to withstand loads in bones of running elephant or to carry the weight of 100 m high redwood tree. Cellular structure of these materials provides the tool for the realisation of optimal combination of properties, e.g., highest stiffness at minimum weight.

The main scope of this paper is to present the possibilities of an artificial cellular material discussing some properties of aluminium foam. Aluminium foam is a metal with cellular structure containing more than 70 vol.% of pores. The combination of metallic character together with cellular structure results in a set of properties which cannot be achieved by any of the conventional treatments of aluminium. Some of them, which give an interesting potential for this material, are briefly outlined in this paper.

## 2. Preparation of aluminium foam

Aluminium foam can be principally produced by two basic preparation methods:

1. Melt processing route involves mixing of foaming agent (metal hydride, e.g. $TiH_2$) into molten aluminium or aluminium alloy. The foaming agent decomposes immediately, releasing gas (e.g., hydrogen), which blows up the melt [2].

2. Powder metallurgical processing employs a gas-tight precompacted mixture (preform) of aluminium or aluminium alloy powder with powdered foaming agent. The preform is expanded into the porous cellular solid by gas which is released from the foaming agent after heating of the preform above the melting temperature of the aluminium matrix [3].

Various techniques [4] based on both principal methods have been investigated in order to achieve uniform cellular structure of the foam at reasonable costs. The main benefit of the powder metallurgical technology recently developed at Institute of Materials and Machine Mechanics SAS [5] in close cooperation with MEPURA [6] is the possibility to use a simple-form precursor, e.g. wire, granulate, etc. for different shapes to be foamed. Using this method diverse aluminium foam parts (panels, profiles, or more complicated 3D-shapes) as well as integral components such as sandwiches or hollow metallic profiles filled with aluminium foam can be produced. The foamed parts are usually covered by dense aluminium skin which significantly improves the mechanical properties (e.g., bending stiffness) and metallic appearance of the foam.

Specimens for testing of properties have been foamed in steel moulds in an electrically heated furnace in the form of plates (140 × 140 × 8.6 mm) or rods (diameter 17 mm, length 300 mm) using foamable wire precursor (diameter of 8 mm). The precursor was hot extruded from the precompacted mixture of various aluminium alloy powders (Al 99.7, AlMg1Si0.6, AlSi12, or AlMg5) and powdered foaming agent (0.4 wt.% $TiH_2$). The test samples have been cut from foamed specimens. Electric discharge machining has been used to reveal the inner pore structure exactly.

## 3. Density

The density of aluminium foam sample was determined simply by a volumetric method (from the weight and the geometry) or computed from the photograph of the inner pore structure. In the second case the pores in machined surface were filled by black resin to establish the contrast between the pores and the pore walls. The samples were then scanned with the resolution of 600 dpi (Fig. 1). Density was computed in various segments of the sample image along both axes (for example 4 segments along $y$ axis, 10 segments along $x$ axis in Fig. 1) using the ratio of the wall area to the whole segment's area. The results are in good agreement with the density obtained by the volumetric method. In contrast to the volumetric method the computer analysis gives also an information about distribution of density in the sample. It can be seen in Fig. 1 that the density in regions closed to the sample surface is remarkably higher than the overall density of the sample. The overall apparent density of various aluminium foam samples was typically found in the range of 0.4–1.2 $g.cm^{-3}$, i.e. the pores filled 65–85% of total volume.

## 4. Pore size

The pores in aluminium foam are essentially spherical and partially closed, although an interconnected or completely closed porosity can be achieved, as well [5]. There exists no typical pore diameter in one sample as can be seen in Fig. 2.

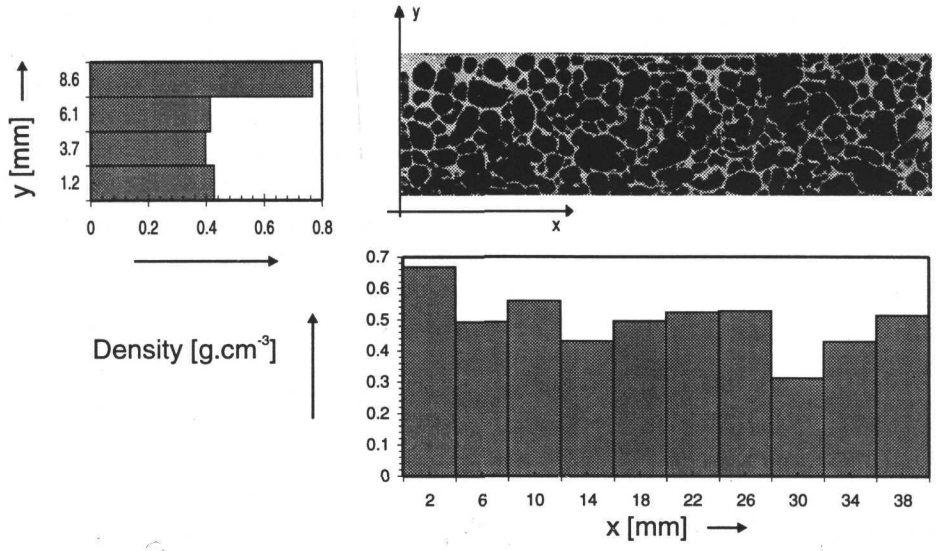


Fig. 1. Distribution of the density in aluminium foam specimen (mean density along $x$ axis = 0.495 g.cm$^{-3}$, mean density along $y$ axis = 0.502 g.cm$^{-3}$, density obtained by the volumetric method = 0.485 g.cm$^{-3}$).

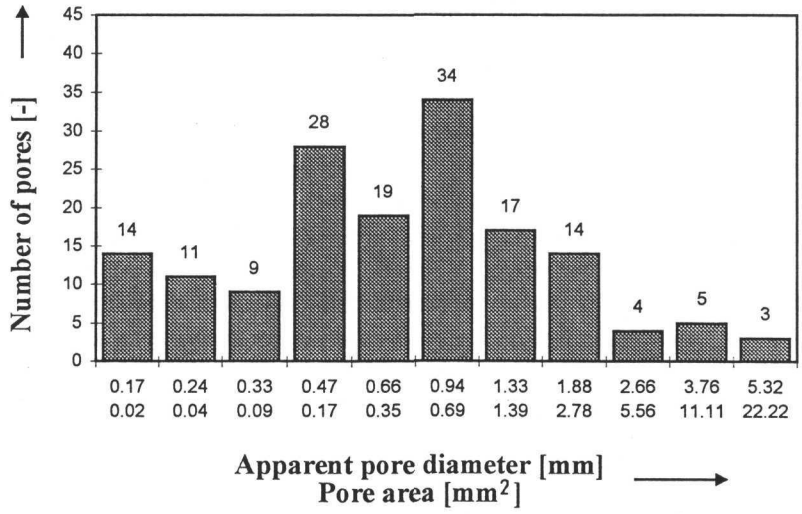


Fig. 2. Distribution of the pore area in aluminium foam specimen (density 0.485 g.cm$^{-3}$, total number of pores = 158, mean pore area = 1.54 mm$^2$, average apparent pore diameter = 1.4 mm).

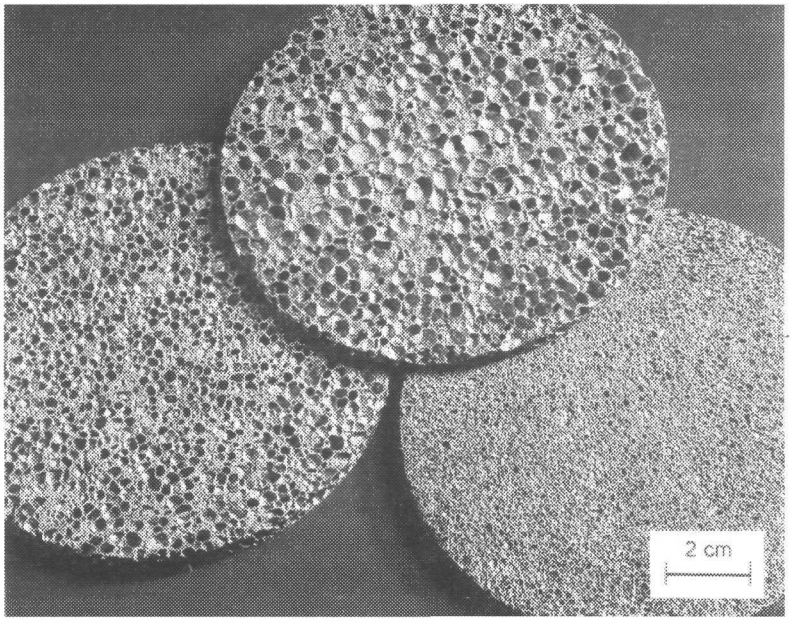


Fig. 3. Aluminium foams prepared from the same AlSi12-alloy with different pore structure (density of all specimens $\approx 0.5$ g.cm$^{-3}$).

Nevertheless, the samples can be prepared with various "average" pore diameters (between 0.5–8 mm) depending on matrix composition or foaming parameters (temperature, time). Three different pore structures prepared from the same alloy (AlSi12) by changing the foaming temperature and time at approximately the same densities are illustrated in Fig. 3.

The size of pores was measured by computer analysis from the scanned sample. For example, the pores in Fig. 1 were distributed into 11 classes according to their square area. The number of pores in each class has been drawn in the diagram (Fig. 2) of the pore size distribution. The apparent pore diameter was calculated from the pore area considering the pore as a circle. However, the pore size distribution is affected by the fact that the interconnected pores (with cracks in the wall) were considered as one pore.

## 5. Behaviour under compressive loading

Static compression tests were performed using 0.01 m.min$^{-1}$ ram speed. Round (diameter 17 mm, length 50 mm) and rectangular ($20 \times 20 \times 8.6$ mm) specimens with various densities were used. Some of the specimens were heat treated (T4,

T5, T6 conditions) according to routines practised in heat treatment of aluminium base alloys.

The compression load-deflection curve of aluminium foam can be divided into three different regions (Fig. 4). At low deflection the material deforms almost elastically (cell walls bend), then a plateau of deformation at approximately constant load exists (cell walls buckle, yield, or fracture) and finally, there is a region of rapidly increasing load after the cell walls crushed together. For the load at the beginning of the second part of the load-deflection curve (plateau), i.e. when significant plastic deformation starts, a stress can be calculated and defined as a plastic collapse stress or as a compression strength.

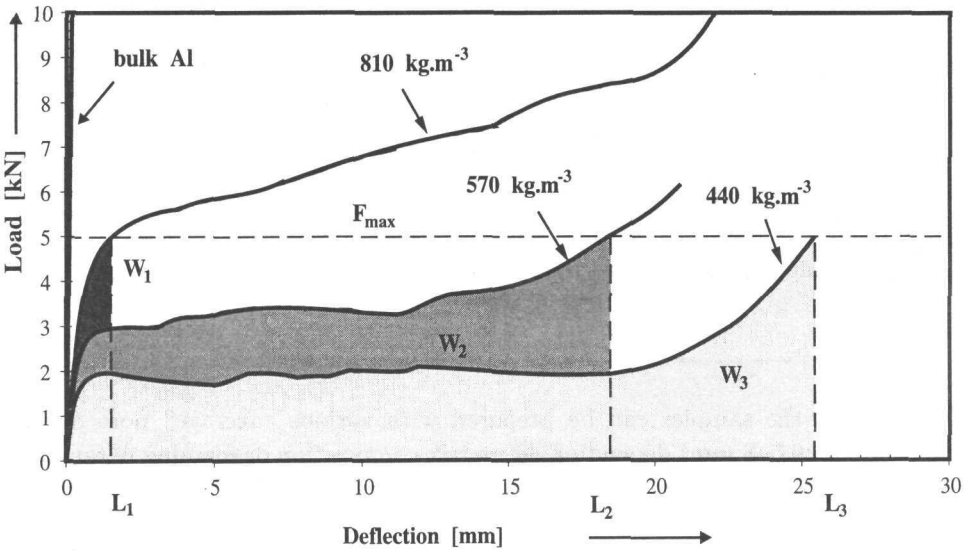


Fig. 4. Compressive load-deflection curves for aluminium foams for various densities prepared from AlMgSi-alloy. The shaded area illustrates the value of the energy $W$ needed for plastic deformation when the load of 5 kN is attained (Note: $W_2 > W_3 > W_1$).

Plastic collapse stress increases with increasing density significantly. It can be improved by an appropriate heat treatment. The collapse mode for aluminium foam, i.e. buckling or breaking of the cell walls, can be influenced by the composition of the base alloy or by the thermal treatment of the foamed part. Foams based on cast aluminium alloys (e.g. AlSi12) tend to the breaking of the cell walls, the wrought alloys tend to the bending and buckling of the cell walls [5].

The area under the load-deflection curve illustrates the energy needed for plastic deformation. The energy used for plastic deformation, until the given load is applied on the foam (e.g. at $F_{max}$ in Fig. 4), is a very important parameter if the impact energy absorption is considered. Also this energy depends strongly on the apparent density. If the density is too low, the foam crushes before impact energy is sufficiently absorbed. If the density is too high, the stress in the foam exceeds given critical value (e.g. $F_{max}$ in Fig. 4) at low absorbed energy.

The representative mechanical properties of some aluminium foams with two different densities are listed in Table 1.

Table 1. Mechanical properties of aluminium foams based on different aluminium alloys

| Composition | Al 99.5 | | AlSi12 | | AlMg5 | 6061 (T1) | | 6061 (T6) | |
|---|---|---|---|---|---|---|---|---|---|
| Apparent density [g.cm$^{-3}$] | 0.57 | 0.85 | 0.54 | 0.84 | 0.80 | 0.54 | 0.81 | 0.53 | 0.80 |
| Plastic collapse stress in compression [MPa] | 3 | 13 | 7 | 15 | 8 | 5 | 15 | 10 | 17 |
| Deformation energy at the compression stress of 20 MPa [MJ/m$^3$] | 3.8 | 4.8 | 5.5 | 0.6 | 3.8 | 5.0 | 0.7 | 6.0 | 0.3 |

## 6. Modulus of elasticity

The elasticity modulus of the aluminium foam cannot be obtained easily from the slope of the stress-deformation curve. This is because the effect of clamping as well as due to the plastic deformation of very thin cell walls in the early stress stage. It is more appropriate to find it from the response of free vibrations of the sample [5].

The rod-shaped sample (diameter of 17 mm, length of min. 300 mm) was vibrated longitudinally using "impact hammer method" according to DIN 53 440. The sample's vibration response shows amplitude maxima for different resonant frequencies corresponding to harmonic oscillation. The elasticity modulus $E'$ was calculated from the resonant frequencies $f_n$ up to the 3rd order according to

$$E' = \rho(2Lf_n/n)^2, \tag{1}$$

where $n$ is the order of resonant frequency in harmonic oscillation, $\rho$ is the density, and $L$ is the length of the sample.

As the storage elasticity modulus $E'$ is almost independent of the resonant frequency [7], it can be considered as a static elasticity value. The elasticity modulus depends strongly on density. The dependence obeys a power law with the exponent of about 1.6 (Fig. 5a). The power-law dependence can be expected from the following consideration: The foam is created by an "infinite" aluminium alloy cluster. The structure of the cluster is defined by the randomly distributed pores filled with gas in the metallic matrix. The presence of such a cluster is essential for the existence of the foam. If the cluster does not exist, the foam disappears and the quantities characterizing some of the effective properties are equal to zero. This situation agrees well with the behaviour of effective properties according to the percolation theory. The effective property becomes zero at percolation threshold. In the case of foamed structure the percolation threshold can be fixed at zero apparent density. It means that the foam exists only at densities above percolation threshold. In this range the dependence of effective properties on the apparent density can be modelled according to the percolation theory, which yields a power-law dependence [8, 9].

The relatively high modulus of elasticity at low density leads to a very high specific stiffness. It can be utilised when the minimum weight of a beam for given

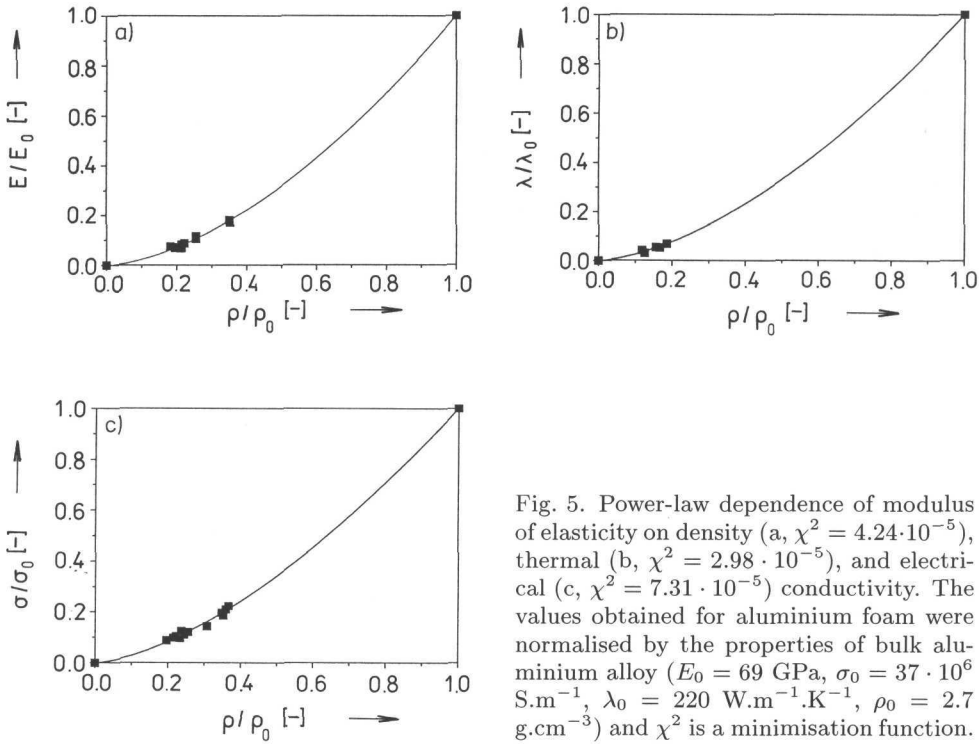


Fig. 5. Power-law dependence of modulus of elasticity on density (a, $\chi^2 = 4.24 \cdot 10^{-5}$), thermal (b, $\chi^2 = 2.98 \cdot 10^{-5}$), and electrical (c, $\chi^2 = 7.31 \cdot 10^{-5}$) conductivity. The values obtained for aluminium foam were normalised by the properties of bulk aluminium alloy ($E_0 = 69$ GPa, $\sigma_0 = 37 \cdot 10^6$ S.m$^{-1}$, $\lambda_0 = 220$ W.m$^{-1}$.K$^{-1}$, $\rho_0 = 2.7$ g.cm$^{-3}$) and $\chi^2$ is a minimisation function.

bending stiffness is required. The material, the beam is made of, should have a large value of $E'/\rho^2$ [1]. Table 2 shows the relevance of aluminium foam for such a purpose.

Table 2. $E'/\rho^2$ values of conventional structural materials in comparison with aluminium foam

| Material | Density $\rho$ [g.cm$^{-3}$] | Modulus $E$ [GPa] | $E/\rho^2$ [$10^{-5}$ GPa.kg$^{-2}$.m$^6$] |
|---|---|---|---|
| Al-foam | 0.5 | 5 | 2.00 |
| Epoxy | 1.3 | 5 | 0.30 |
| Steel | 7.8 | 210 | 0.35 |
| Aluminium | 2.7 | 69 | 0.95 |
| Glass | 2.5 | 70 | 1.12 |
| Concrete | 2.5 | 50 | 0.80 |

## 7. Thermal and electrical conductivity

The thermal conductivity was tested by the comparative method for different temperatures up to 400 °C using cylindrical specimens with different densities prepared from various Al-alloys. The outer surface of the samples (diameter 25 mm, length 20 mm) was removed by the electric discharge machining to eliminate the influence of surface skin. The electrical conductivity was calculated from the geometry and the resistance of the sample which was measured by the four point method. Cylindrical specimens (diameter of 17 mm, length of 300 mm) with various densities were used.

Both thermal and electric conductivity of aluminium foam depend on the density significantly. If the experimental values are normalised by the properties of basic alloy, the dependence obeys the power law with the exponent from 1.48 to 1.60 (Fig. 5b, 5c). The similar exponent found for the electrical and thermal conductivity confirms the validity of Wiedemann-Franz law for aluminium foam. The power-law dependence of transport properties on the density agrees surprisingly very well with the behaviour of the elasticity modulus. It implies that the modulus of elasticity of the aluminium foam belongs to the same universality class as its thermal and electrical conductivity [10].

## 8. Sound absorption

Sound absorbing material performance is defined by the coefficient of sound absorption $\alpha$, which is the ratio of the dissipated sound intensity in the surface

to the incident sound intensity. This coefficient depends on frequency and angle of incidence. The measurement of absorption coefficient $\alpha$ was performed in an impedance tube (diameter of 99 mm and 29 mm – Type 4002 Brüel & Kjaer) according to DIN 52 215 using foam specimen with an open porosity at the density of 0.48 g.cm$^{-3}$. The thickness of the test specimen was 8.6 mm.

Aluminium foams, especially those with interconnected pores, are highly efficient in sound absorption; incoming sound is interfered among the pores inside the foam, the pore surfaces vibrate converting the sound into heat. A considerably reduced sound level is reflected back into the enclosed space. The absorption coefficient is a function of material thickness, foam density, and pore size. The higher is it, the finer is the porosity, and the more interconnected is the pore structure. Comparison of sound absorbing performance of aluminium foam specimen with other sound absorbing materials is given in Fig. 6. Maximum sound absorption can be adjusted for preferred frequencies by the thickness of absorbing material (enlarging the thickness shifts the $\alpha$-maximum toward lower frequencies). The same effect can be achieved if an air gap is created between the absorber and the solid background. Aluminium foam in comparison with other absorption materials such as glass, or mineral wool fibres, or polymer foams is very stiff and therefore suitable for this application; there is no need for any supporting construction. Thus, it can provide sound absorption at low frequencies at a smaller absorbent thickness using the air gap. Moreover, it combines the absorbing performance and cover sheet function

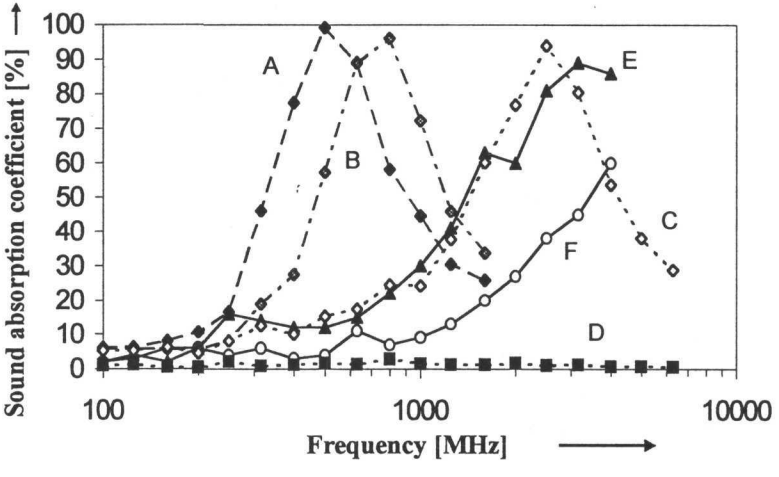


Fig. 6. Sound absorption coefficient of aluminium foam at various thicknesses of the air gap between the sample and the solid background (A = 40 mm, B = 20 mm, C = 0 mm) compared with bulk aluminium (D), PU-foam (E), and glass fibre mat (F).

in one material, is non-flammable, does not erode under air flow or vibration, and can be easily cleaned if contaminated with dust.

## 9. Electromagnetic shielding

Electromagnetic wave shielding is used to protect electronic devices and room interiors from the negative influence of electromagnetic waves. The ability to reflect the electromagnetic energy can be defined by the shield effectiveness. Measurement of electric and magnetic shield effectiveness at frequency range 0.1–1000 MHz was done by KEC method. Aluminium foam sheets (140 × 140 × 8.6 mm) with the density of 0.51 g.cm$^{-3}$ were used as the test specimens. The bulk aluminium sheet (140 × 140 × 2 mm) and silicon steel sheet (140 × 140 × 0.5 mm) were used as the reference materials.

Aluminium foam possesses good electric conductivity to minimise the penetration of electromagnetic waves into the material and low magnetic permeability to convert magnetic energy into the heat. The magnetic field shielding effectiveness of aluminium foam specimen is superior in comparison with bulk aluminium and silicon steel of the approximately same weight for frequencies above 200 kHz (see Fig. 7).

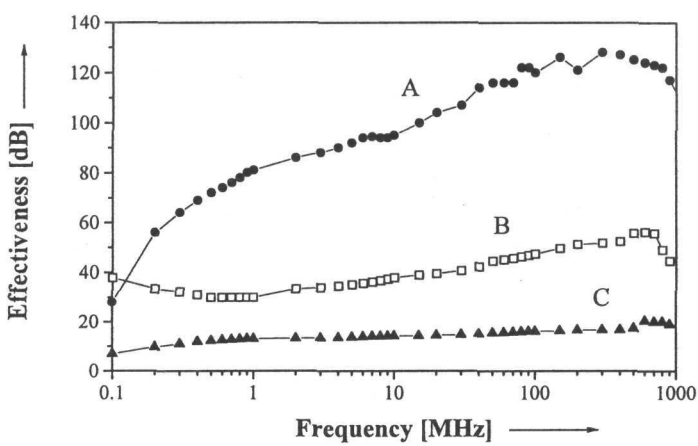


Fig. 7. Magnetic field shielding effectiveness as a function of frequency for aluminium foam (A), Si-steel (B), bulk aluminium (C) at the same weight of the samples.

## 10. Potential applications

The unique combination of apparently concurrent properties in one homogeneous material opens a variety of potential industrial applications such as:

- self supporting, stiff, and super light weight panels for buildings and transport
- non-flammable ceiling and wall panels with improved thermal and sound insulation
- impact energy absorption parts for cars, lifting, and conveying systems
- permanent cores for castings instead of sand cores
- isotropic sandwiches
- machine casings with improved sound and vibration damping
- fillings in hollow materials against buckling
- heat exchangers, filters, catalysts
- heat shields and encapsulators
- floating structures for elevated temperature and pressure
- housings for electronic devices providing electromagnetic and heat shielding
- sound absorbers for difficult conditions (high temperature, moisture, dust, flowing gas, vibrations, sterile environment).

## 11. Conclusions

Some of the properties and potential applications of aluminium foam have been presented. This ultralight material possesses high stiffness at very low density, it absorbs high impact energies regardless of the impact direction (is isotropic), has very low thermal conductivity, is highly efficient in sound absorption, electromagnetic shielding, and vibration damping.

Although the properties of aluminium foam depend also on the shape, size, and uniformity of the pore distribution inside the matrix, they are predominantly influenced by apparent density of the foam. There is a fairly close relationship between its density and some of its properties. This dependence obeys the power law

$$K = K_0(\rho/\rho_0)^m,$$

where $K$ is the property and $\rho$ is the density of the foam, while $K_0$ and $\rho_0$ are the corresponding properties of bulk aluminium alloy. It was shown that the exponent $m$ for aluminium foam lies usually in the range of 1.5–1.7.

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