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Aluminium Foams for Automotive Applications

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Abstract

A powder metallurgical method which allows for the production of aluminium foams with porosity levels up to 90% is described. The foams have closed pores and densities ranging from 0.4 to 1 g/cm^3. The unique mechanical properties of metal foams are described. The density dependence of metal foam properties is shown with the flexural strength as an example. The discussion then focuses on the energy absorption properties of aluminium foams and tools to select appropriate foams for a given energy absorption task.

1. Introduction

Foamed materials are widespread in automotive applications. Whereas polymer foams have been applied for many years, foamed metals are just beginning to move into the focus of interest. As a rule, the growing demands for active and passive safety of vehicles, particularly in the automotive industry, lead to an increase of vehicle weight. But this is contrary to further demands, e. g. for a possibly lower fuel consumption. For this reason, materials of low specific weight and high energy absorbing capacity are of special interest. Foamed organic materials have a low specific weight, but the energy amounts convertible to deformation energy are also relatively low as polymer foams have small strengths only. Applying aluminium foams, energy absorbing devices with a corresponding higher energy level can be realised.

2. Manufacturing of aluminium foams

Using a powder metallurgical process, metallic foams can be produced in an elegant way [1,2]. For this, customary powders of aluminium or aluminium alloys are mixed by applying conventional techniques - for example in an asymmetrically moved mixer - with low quantities of a likewise powdered foaming agent. Thus, a homogeneous distribution of the gas releasing substance in the powder mixture is realised. Afterwards, this powder mixture is compressed to a semi-finished product of nearly vanishing porosity. Depending on the intended application, different compression techniques are used. As a rule, direct powder extrusion is recommended, whereas uniaxial hot pressing is often used for test series in laboratories. Other methods such as powder rolling or hot isostatic pressing have turned out to be feasible as well, but they are more complicated and therefore only used for special applications.
Provided that correct process parameters have been chosen, the result of the compression process is a foamable semi-finished product that expands during a final heat treatment at a temperature above the melting point of the corresponding alloy. This way the material develops its highly porous structure consisting of closed cells. This implies that within the foamable semi-finished product each particle of the foaming agent must be embedded in a gas-tight metallic matrix. Otherwise, the evolving gas could escape prior to the beginning of the expansion through existing interconnected pores and, thus, would no longer be effective in producing and developing pores. The result of a successful foaming process is seen in Fig. 1. The expansion has been driven to its maximum thus yielding a multitude of irregularly shaped cells with thin walls.
The foamable semi-finished product can be worked into sheets, rods, profiles, etc. by applying conventional techniques such as rolling, forging or extrusion prior to the actual foaming. It is possible to manufacture relatively complex shaped parts by filling adequately shaped hollow

moulds with the foamable material and then heating up both the mould and the foamable material to the required temperature.

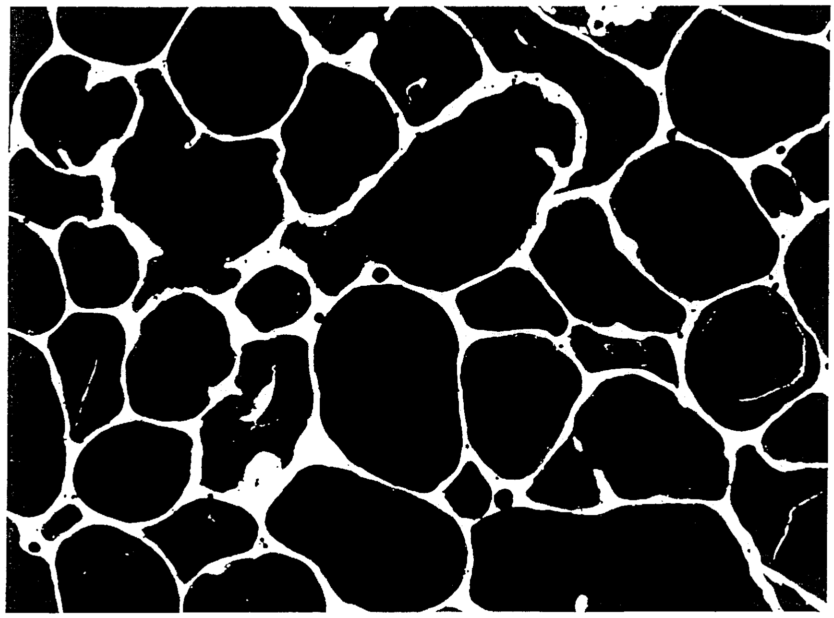

Fig. 1: Cell structure of an aluminium foam (9:1)

3. Properties of aluminium foams

Foamed materials in general and aluminium foams in particular show a number of interesting features due to their porous structure and open a wide range of applications. Metal foams combine properties which arise from the metallic nature of the matrix with the behaviour due to their morphology. The following list includes the most interesting properties of aluminium foams which are of importance for users in transport applications. Also, some references are given:

- nearly closed porosity
- low specific weight [2]
- high energy absorption capacity during plastic deformation [3]
- high specific stiffness [9]
- reduced thermal and electrical conductivity [4]
- good mechanical [7] and acoustic damping [10]
- not inflammable
- recyclable
- good machinability

An example for some of the properties of aluminium foams is given in Table 1 for two foams made of different alloys and having different densities.

An obvious fact is that most properties depend strongly on the density of the foam and the properties of its matrix material. Foams with a higher density, e.g., have higher compression strengths and foams made of high strength aluminium have higher compression strengths than those made of low strength aluminium.

Table 1: Properties of aluminium foams (typical values, all measured at 20°C). For comparison: conventional massive aluminium

alloy		Al99.5 foam	AlCu4 foam	Al99.5 massive
general data				
foaming agent	-	TiH_2	TiH_2	-
heat treatment of foam	-	none	hardened	-
density	g/cm^3	0.4	0.7	2.7
mean pore diameter	mm	4	3	-
mechanical properties				
compression strength	MPa	3	21	-
energy absorption at 30% strain	MJ/m^3	0.72	5.2	-
	kJ/kg	1.8	7.4	-
Young´s modulus	GPa	2.4	7	67
dynamical loss factor (1 kHz)	1	$25 \cdot 10^{-4}$	--	$<5 \cdot 10^{-4}$
electrical and thermal properties				
electrical conductivity	$m/(\Omega \cdot mm^2)$	2.1	3.5	34
specific electrical resistivity	$\mu\Omega \cdot cm$	48	29	2.9
thermal conductivity	$W/(m \cdot K)$	12	--	235
thermal expansion coefficient	1/K	$23 \cdot 10^{-6}$	$24 \cdot 10^{-6}$	$23.6 \cdot 10^{-6}$

Many properties obey a power law of the type:

$$A(\rho) = c \cdot \rho^n$$

Here A is the quantity of interest, c is a constant, ρ is the density and n is an exponent which is usually in the range between 1.5 and 2. Examples for such power-laws have been measured for the compression strength, conductivity and Young's modulus by various authors [2,4-6,10]. Fig. 2 shows the flexural strength of AlMg3 foams as a function of density. In this case the exponent is about 1.7.

4. Energy absorption of aluminium foams

Up to now, polymer foams or honeycomb structures are used in energy absorbing structures. The possibility of controlling the behaviour of stress and strain by an appropriate selection of matrix material, cellular geometry and relative density makes foams an ideal material for such applications [8]. Decisive for the quality of packing protections or energy absorbers is the feature of being able to absorb energy without the maximum stress or the highest occurring acceleration exceeding the upper limit at which damages or injuries occur. Compared to foamed organic materials, metallic foams are more advantageous if, due to a small available design space, a higher deformation stress with the same or uprated energy absorption is requested.

Fig. 3 shows the deformation behaviour of foamed aluminium under compressive load. The energy per volume absorbed by the material corresponds directly with the area under the respective stress-strain curve. The foam shows a constant deformation stress and therefore can absorb much more deformation energy than a piece of massive aluminium when both are loaded up to a given limited stress level. The major part of the absorbed energy is irreversibly converted into plastic deformation energy which is a further advantage of foamed aluminium. At the same stress level the dense matrix material is deformed in the regime of reversible linear-elastic stresses and releases most of the stored energy after the load has been removed.

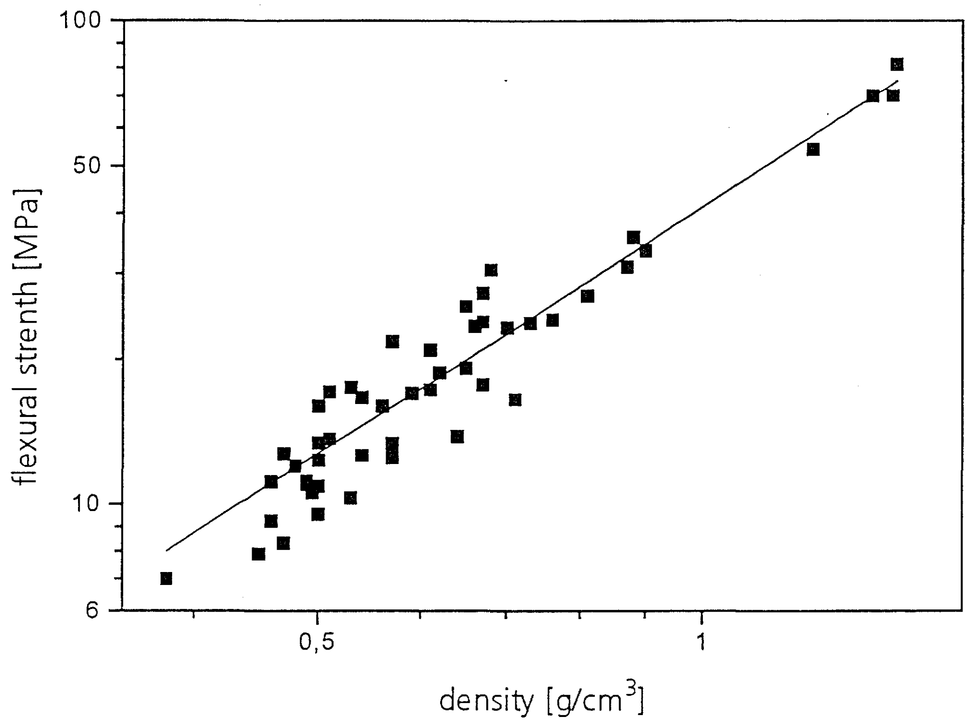

Fig. 2: Flexural strength of AlMg3 foams.

This elastic behaviour of a dense material is especially disturbing in applications where a controlled impact energy absorption without repercussion is requested as for example in automobile crush zones.

As aluminium foams can be produced in a relatively wide spectrum of densities and properties [2], the question arises which foam is the most suitable one for a given energy absorption task. For the selection of the appropriate energy absorbing materials, analytical methods can be applied which relate the demands and the foam parameters. The analytical techniques presented briefly in the following describe the interrelationship between foam features and energy absorbing characteristics of aluminium foams taking data as a basis which has been determined in quasi-static compression tests of AlSi12-alloy foams. For a more detailed description of the typical testing parameters and the experimental set-up, see Ref. [4].

4.1 Efficiency of energy absorption

The energy absorption efficiency compares the deformation energy absorbed by a real material or component with that of an "ideal" energy absorber. An "ideal" absorber shows a rectangular march of the load-compression curve, i. e. it reaches directly the maximum admissible strain and keeps it constant during the whole deformation process. The efficiency η is defined as ratio of the actually absorbed energy after a compression strain s and the energy absorption of the ideal absorber:

$$\eta = \frac{\int_0^s F(s')ds'}{F_{max}(s)s}$$

where $F_{max}(s)$ is the highest force occurring up to the deformation s.

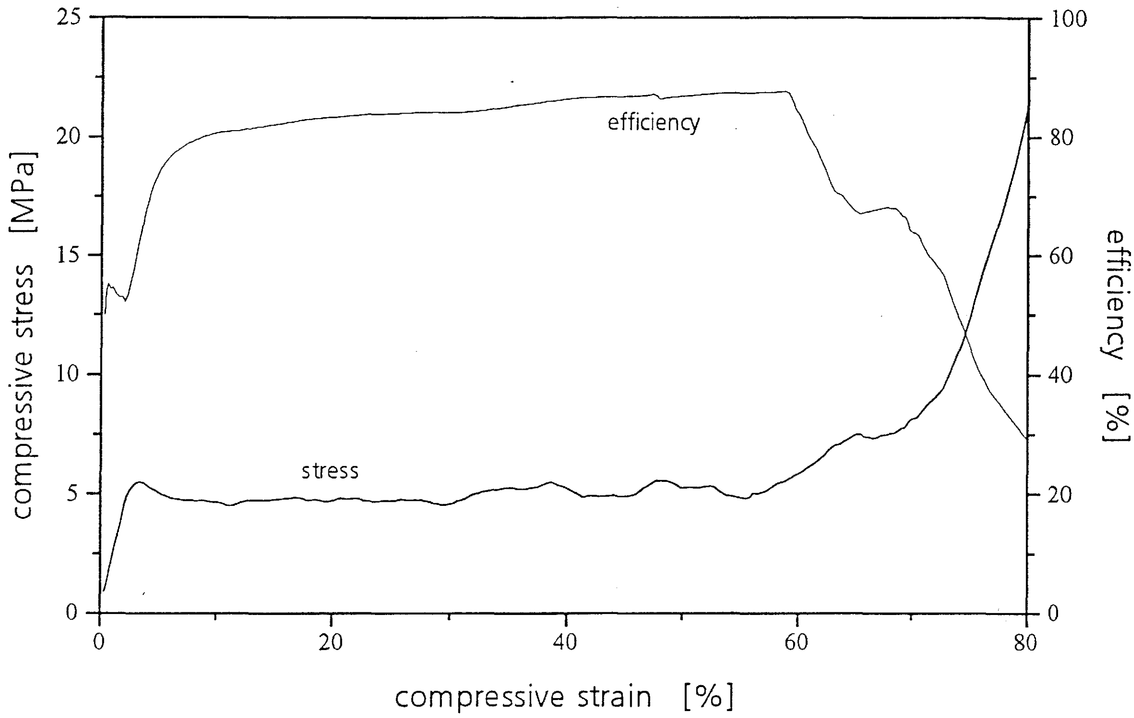

Fig. 3: Compression stress and energy absorption efficiency of an AlSi12 foam (ρ=0.36 g/cm^3)

As all real materials show a varying stress under compression, the calculated efficiency also changes during the deformation process and therefore depends on the nature of the load-compression curve. Depending on density and alloy composition, the foamed aluminium reaches efficiency values of up to 90% especially for the first 50% of deformation. The relative density, the cellular morphology, the foam homogeneity as well as density gradients influence considerably the length of the plateau during compression. In the area of densification, the efficiency decreases with increasing stress. It can be said that foams can be loaded optimally only until the end of the plateau area in the stress-strain curve. Fig. 3 shows the stress-strain curve of an AlSi12 foam with the numerically determined efficiency (right scale in the diagram).

The energy absorption efficiency is a valuable parameter in characterising a given test specimen with respect to its energy absorbing features and allows to draw conclusions from general foam properties to the deformation behaviour. However, for the selection of an appropriate material for a given energy absorption problem, the efficiency by itself is not sufficient.

4.2 The energy absorption capacity

Especially concerning the construction of vehicles, the space and weight required for additional structural components is of high importance. The absorbed impact energy per initial volume of the energy absorber is therefore of special interest and is shown in Fig. 4 as a function of foam density. The three curves show the absorbed deformation energies after compression strains ε, of 20 %, 40 % and 60 % and are calculated from the data of compression tests [4].

As expected, a strong increase of the deformation energy can be observed going from low to high densities. However, the crucial parameter describing the usefulness of an energy absorber is the maximum stress occurring during compression. Therefore, the various pieces of information are condensed into one presentation as follows.

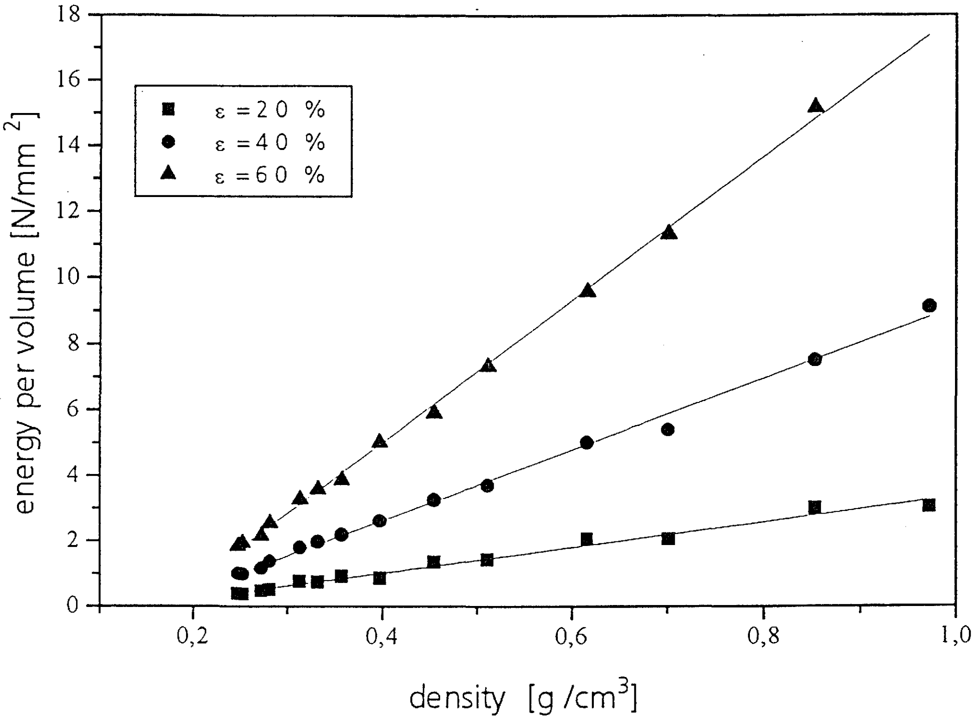

Fig. 4: Energy per unit volume absorbed by various AlSi12 foams after compression strains ε of 20 %, 40 % and 60 %.

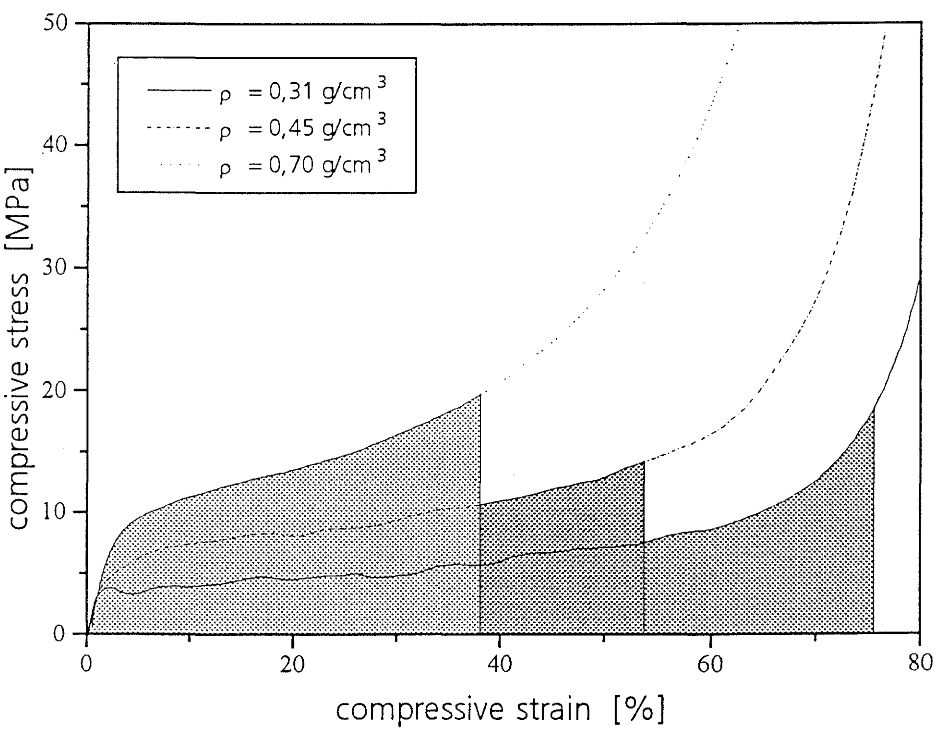

Fig. 5: Compression behaviour of three AlSi12 foams of various densities. The various shaded areas correspond to same absorbed amount of energy W.*

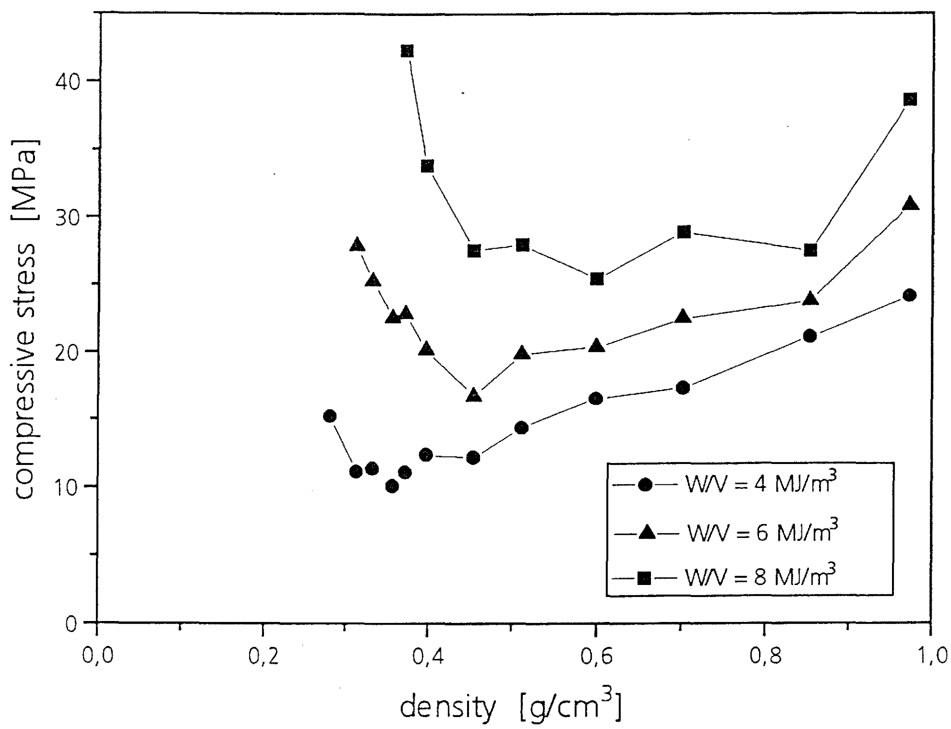

Fig. 6: Maximum stress occurring when a given deformation energy is absorbed by foams of various densities.

4.3 The energy absorption diagram

Maiti et al. [8] have developed the present methods and proposed energy absorption diagrams for the determination of optimised energy absorbers. Here it is presumed that a near-ideal foam absorbs a given energy at a minimum stress. Fig. 5, showing the compression behaviour of three foams of various densities, explains these facts in detail.

The shaded areas correspond to an equal amount of energy W* absorbed by the three foams. The right margin of each of the shaded areas marks the compression which is necessary to absorb this amount of energy. In the case of the lowest density, the stress-strain curve has already passed through the regime of constant stress before the energy W* has been absorbed and therefore, the stress reaches high values. On the other hand, the foam of the highest density hardly shows a plateau area with constant stress at all and has a higher maximum stress, too. In contrast, for the given impact energy W*, the foam of the medium density is loaded exactly up to the end of the plateau area. Therefore, it shows the lowest peak stress up to full energy absorption. In this way, for each given impact energy a foam of a specific density can be determined showing the lowest possible maximum stress during deformation.

Finally, Fig. 6 shows the maximum stress occurring when a given deformation energy is absorbed by foams of various densities. With decreasing energy absorption, the minimum of the curves in Fig. 6 is shifted to lower foam densities. Again it can be seen, how for various given energy densities and maximium permitted impact stress levels an appropriate foam can be selected.

5. Prospects

As described above, there are various techniques for the selection and evaluation of energy absorbers made of foamed aluminium. But it has to be emphasised that a simple foam structure does not necessarily present an optimum energy absorption element. By integrating such elements into the whole body structure, these elements could be tailor-made insofar that the deformation behaviour of the whole structure permits an efficient dissipation of energy. For example, it is possible to use integral foams or composite materials made of foamed aluminium and conventional materials and to improve the very good energy absorption capacity of the aluminium foam this way. This does not only apply to the frontal collision but also to the side impact protection. By selecting the alloy and possibly also the heat treatment condition, it is possible to influence besides the failure criteria (not ductile/ductile) also the stress level. For the development of highly efficient energy absorbers, aluminium foams represent an ideal technological basis.

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