IFAM
Fraunhofer Institut
Fertigungstechnik
Materialforschung

FOAMINAL®

Properties Overview and Design Guideline

Version 1.4

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The Process

At the Fraunhofer Institute for Manufacturing and Advanced Materials (IFAM), a powder-metallurgical process for the production of foamed metals has been developed (Fig. 1). Aluminium foams produced according to this patented method carry the trademark FOAMINAL®. The process allows for the production of near net-shape parts as well as 3d-shaped sandwich structures with a foamed core layer, aluminium alloy or steel face sheets and metallic bonding between the latter and the core.

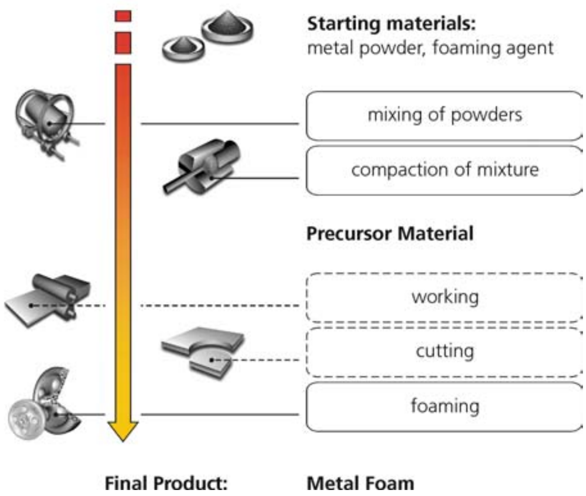

Fig. 1: IFAM process for production of metal foams

Processing

At IFAM Bremen several types of furnaces are avaiblable for expansion of foamable precursor material. In most cases batch furnaces with forced air circulation will be employed. In special cases a continuous belt furnace or an induction furnace are also available (please contact us for more details).

Foaming temperatures:

- Aluminium (Alloys): 590°C – 750 °C
- Zinc (Alloys): 420°C – 600 °C

Geometrical Restrictions:

- max. length x width x height: 1000 x 500 x 400 mm^3
- max. foam weight: approx. 50 kg

FOAMINAL® parts can be mechanically cut using all the methods available for conventional parts (e.g. turning, milling, sawing). Forming is usually not required, as the process leads to near net-shape parts. Possible joining techniques include adhesive bonding, welding (e.g. laser welding) and brazing. Joining using screws can be based on threaded inserts or realised directly by using wood screws. To provide for special surface qualities or properties, additional layers of material can be applied by means of thermal spraying.

FOAMINAL® - Products

FOAMINAL® parts (Fig. 2) are integral metal foams with a closed cell structure and a closed surface (like gravity die casting parts). This so called skin has an influence on some mechanical properties of the part (e.g. stiffness).

FOAMINAL® products are available in basic geometries like cylinders, blocks or plates. In addition, near net-shap parts with complex geometries can be produced. Fundamental properties of these are:

- density 0.4 (without skin) ... 1.0 g/cm^3
- average pore diameter 2 ... 6 mm
- closed cells
- closed surface skin
- surface quality similar to gravity die casting

Fig. 2: Examples of FOAMINAL® parts

General

Properties of FOAMINAL® can be customised by variation of one or more of the following parameters:

- density/porosity
- pore morphology
- alloy composition
- heat treatment

Most properties of metal foams can be approximated on the basis of the relative density of the foam and a constant for the property considered. These main poperties can be calculated according to a power law:

$$\text{Property}_{\text{Foam}} = \text{Constant}_{\text{Property}} * \left(\rho_{foam} / \rho_{solid} \right)^{n}$$

The FOAMINAL® parts are not purely isotropic. The manufacturing process of the foamable precursor material causes a main expansion direction (indicated with the index “S”).

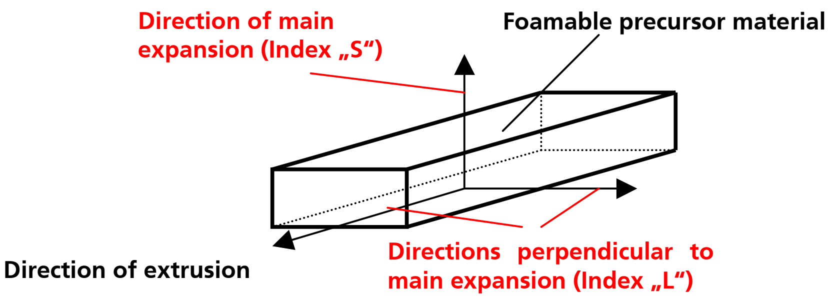

Fig. 3: Expansion directions of IFAM foamable semi-finished material

Young's Modulus

The measurement of the Young's modulus in destructive tensile or compressive testing is complicated due to the limited elastic deformation of metal foams. A non-destructive testing method is vibration analysis which leads to the following values.

Density	g/cm^3	0.5	0.6	0.7	0.8
Young's Modulus	GPa	3.5	4.9	6.6	8.4

Table 1: AlSi12 foam - Young's Modulus in depence of foam density

The given values are calculated with the following approximation which is based on experimental results on AlSi12 foams.

$$E_{Foam} = Constant_{Young's\ Modulus} * \left(\rho_{foam} / \rho_{solid} \right)^n \qquad 1.7 \le n \le 2.3$$

Figure 4 shows that for AlSi 12 foams the given equation is an excellent approximation.

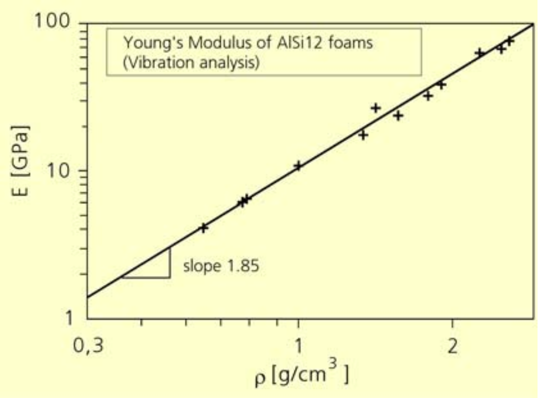

Fig. 4: Young's Modulus of AlSi12 depending on the foam density

(E.g. $Constant_{Young's\ Modulus} = 8 \times 10^4$ MPA, n = 1.85 for AlSi12)

Compressive Strength

In Fig. 5 a good example for the general behaviour of metal foams under compressive loads is given. The maximum load is followed by a not necessarily distinct drop in compressive stress until the so-called plateau region is reached. At this stage the compressive stress is almost constant for large compression ranges. Finally the compressive stress increases again caused by a strong densification of the metal foam.

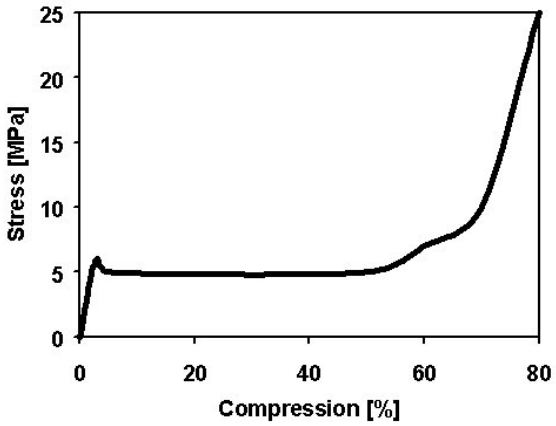

Fig. 5: General stress – compression curve for metal foams

The stress level of the plateau region is the characteristic compressive stress for each matrix material and foam density.

Material	AlSi7	AlSi12	AlSi12	AlSi12	AlMg1Si (6061)	AlMg1Si (6061)	AlMg1Si (6061)
Testing direction	S	L	L	S	L	L	S
Surface skin	removed	removed	not removed	removed	removed	not removed	removed
Density [g/cm^3]	Compressive Strength [MPa]						
0.5	7.9	13.9	11.1	11.6	14.3	14.1	9.0
0.6	11.9	18.8	16.1	15.1	22.0	20.6	12.6
0.7	16.9	24.3	22.1	18.9	31.8	27.5	16.7
0.8	22.8	30.2	29.0	23.0	43.6	35.8	21.4

Table 2: Compressive strength of aluminium foams with different matrix alloys

These values are calculated with the following power law based on experimental results.

$$\sigma_{compr/foam} = Const_{compr.} * \left(\rho_{foam} / \rho_{solid} \right)^{n} \qquad 1.5 \leq n \leq 2.5$$

Fig. 6 shows that the given approximation is in good agreement with test results.

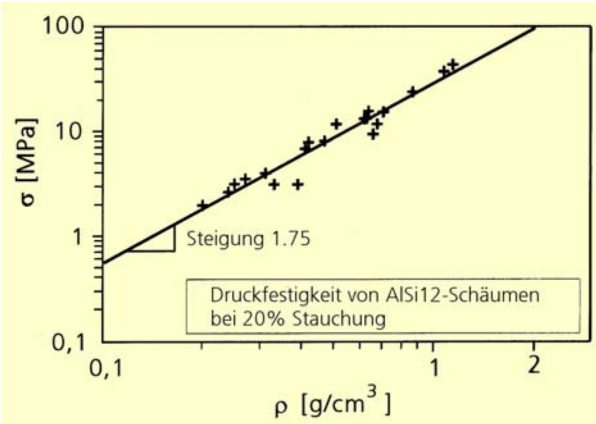

Fig. 6: Compressive stress – density curve for AlSi12 foams

Table 3 gives an overview of available approximation parameters for chosen aluminium foams.

Material	AlSi7	AlSi12	AlSi12	AlSi12	AlMg1Si (6061)	AlMg1Si (6061)	AlMg1Si (6061)
Testing direction	S	L	L	S	L	L	S
Surface skin	removed	removed	not removed	removed	removed	not removed	removed
$Const_{compr.}$ [MPa]	361	225	347	134	789	398	198
n	2.27	1.65	2.04	1.45	2.38	1.98	1.83

Table 3: Compression parameters for aluminium foams

Energy Absorption

The energy absorption of a metal foam can be determined in compressive testing. In Fig. 7 a force – compression distance curve for a metal foam is displayed. The amount of absorbed energy is the integral of the compressive force by the compression distance. For comparsion of different materials as energy absorbers the efficiency is a well established measure. At a defined deformation the efficiency is the quotient of the absorbed energy and the product of the maximum force and the deformation length.

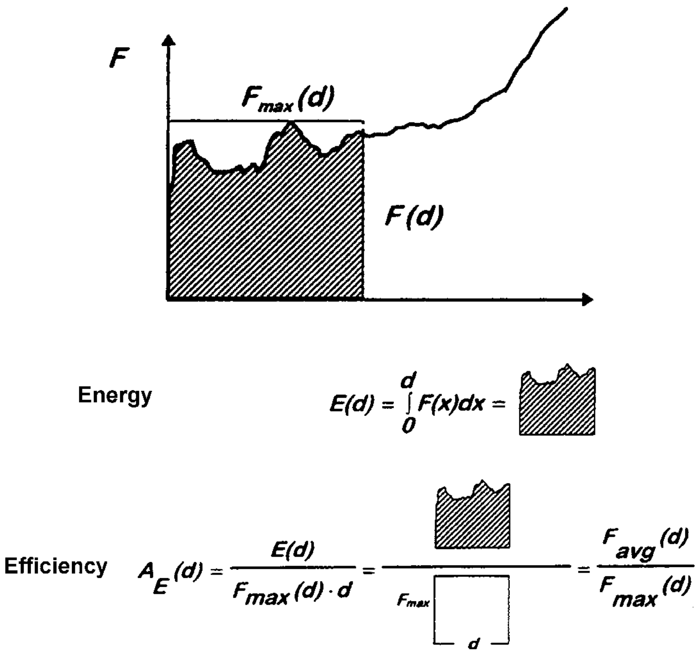

Fig. 7: Energy absorption and efficiency

FOAMINAL® parts can be produced with different foam densities which results in different energy absorptions (Fig. 8). The shaded areas underneath the stress – strain curves indicate equal amounts of absorbed energy.

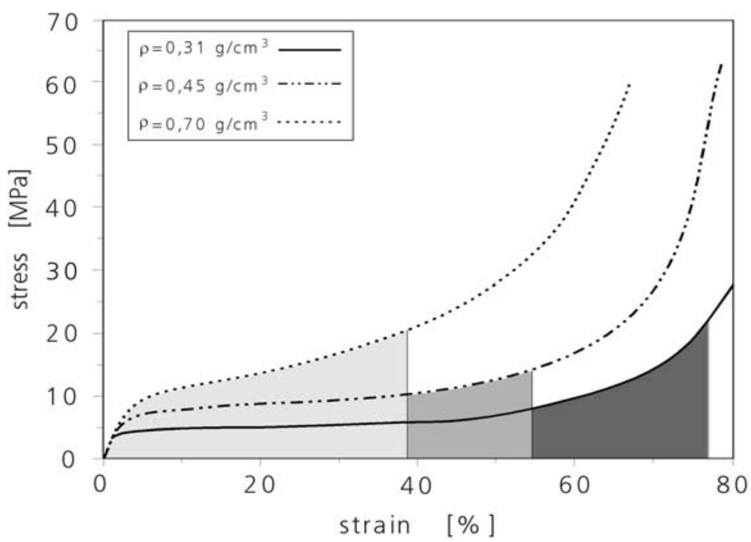

Fig. 8: Energy aborption of metal foams with different densities

It is obvious that the sample with the lowest foam density needed to be compressed further than the samples with middle and highest foam density to absorb the same amount of energy. In terms of maximum stress the sample with the lowest density nearly reached the stress level of the one with the highest density. This clearly indicates that for the design of energy absorbers several parameters have to be taken into account:

- acceptable maximum force
- maximum deformation length
- amount of energy to be absorbered

Depending on the above mentioned requirements the geometry and the foam density of a FOAMINAL® part can be designed to achieve an application tailored energy absorber.

Table 4 contains single values of energy absorption for different matrix alloys and foam densities.

Alloy composition	AlMg1SiCu (6061)	AlMg1SiCu (6061)	AlSi7	AlSi7	AlSi12
Heat treatment	age hardened	„as foamed“	„as foamed“	„as foamed“	„as foamed“
Density [g/cm^3]	0,6	0,6	0,55	0,63	0,6
Energy absorption (50% strain) - by volume [kJ/dm^3] - by mass [kJ/kg]	 7.9 13.2	 7.1 11.9	 4.4 8.0	 5.3 8.4	 3.1 5.3
Efficiency of energy absorption - 20 % strain - 50 % strain	 83.8 75.3	 86.1 80.7	 85.6 85.8	 83.4 84.0	 - -

Table 4: Energy aborption of metal foams

Static and Dynamic Compression Tests

Under compressive loads FOAMINAL® parts show no strain-rate effect in compressive strength.

Test no.	Foam density (g/cm^3)	Impact velocity (m/s)	Average stress at 50% def. (MPa)
S1	0.34	Static (20mm/min)	5.6
S2	0.23	-	4.3
S3	0.32	-	6.0
S4	0.36	-	7.5
S5	0.38	-	7.9
S6	0.40	-	7.7
S7	0.47	-	13.8
D1	0.40	15.8	9.8
D2	0.40	15.9	11.0
D3	0.40	15.5	9.9
D4	0.43	15.9	10.8
D5	0.41	15.8	10.1
D6	0.42	16.1	9.7

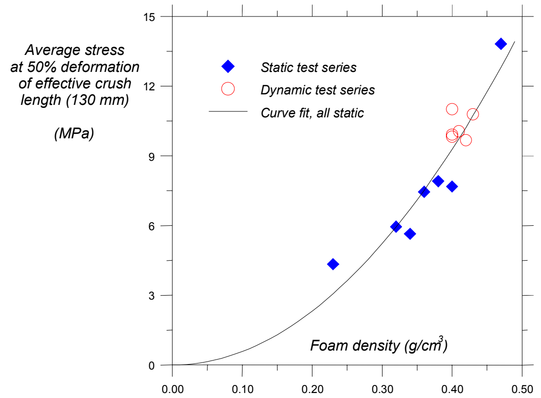

Fig. 9: Static and dynamic compressive strength[1]

[1] Tests performed at Dept. Of Structural Engineering, Norwegian University of Science and Technology (NTNU)

Fatigue:

Compression-tension fatigue test curves for AlMg1SiCu alloys (6061) have been determined with a load ratio R = -1. In Fig.10 density specific load versus number of cycles are shown.

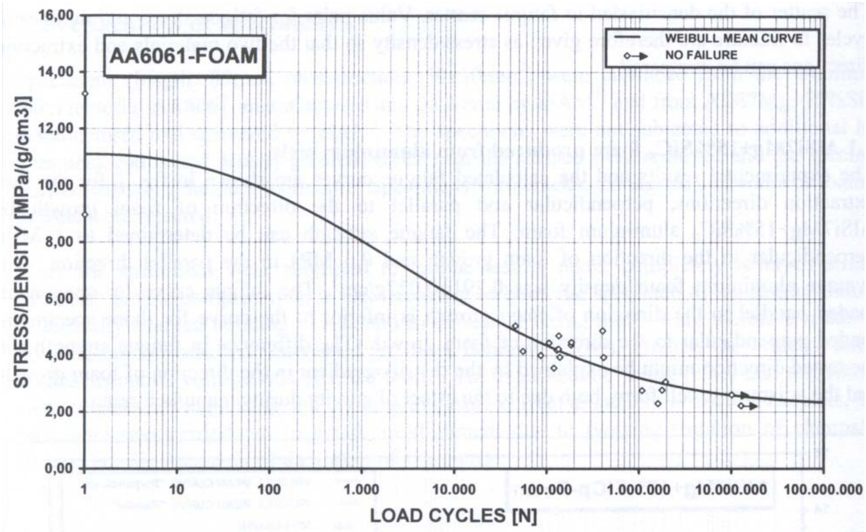

Fig. 10: Weibull mean curve of compression-tension fatigue test of 6061 foam[2]

Compression-compression S-N curves for AlMg1SiCu alloys (6061) in two different heat treatment states have been determined on cylindrical foam samples with a load ratio R = 0.1. Individual measurements are given in Fig. 11 (left diagram), in which arrows denote samples that survived further testing to 10^7 cycles. Average values derived from the individual measurements are also given in the diagram to the right.

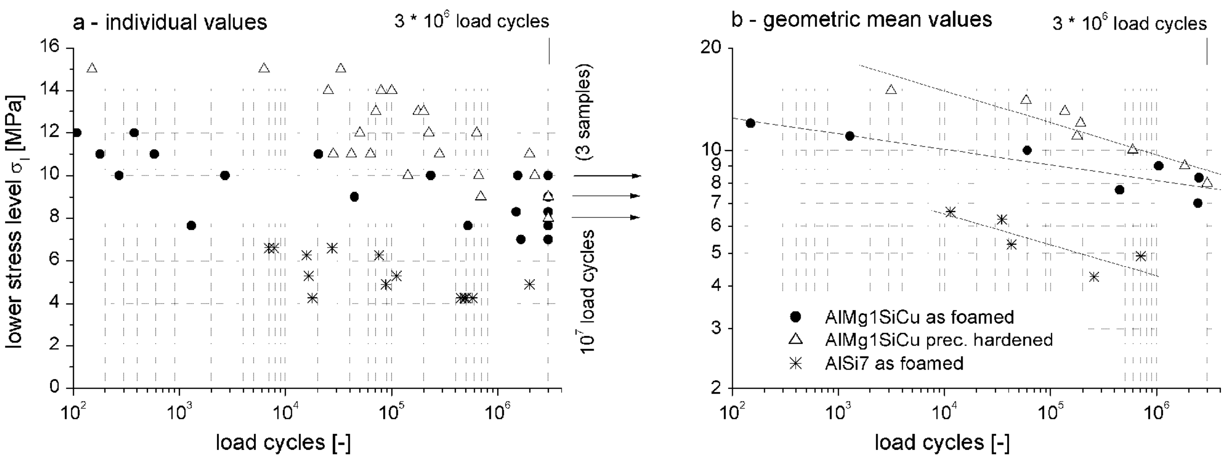

Fig. 11: Compression-compression fatigue of 6061 foams[3]

[2] „Fatigue behaviour, strength and failure of aluminium foams“
Schultz et al. in „Metal Foams and Porous Metal Structures“ MIT 1999
[3] “Influence of heat treatment on compression fatigue of aluminium foams“,
D. Lehmhus et al. submitted to Journal of Materials Science, July 2001, ref. no. JMSC8855-01

Shear Strength

General Approximation:

$$\tau_{Foam} = Const_{shear} * \left(\rho_{foam} / \rho_{solid} \right)^{n} \qquad 1.7 \leq n \leq 2.3$$

In Fig. 12 an approximation for AlSi12-foam samples with different densities is displayed. Additionally single values for AlSi12 as well as 6061 are given in Table 3.

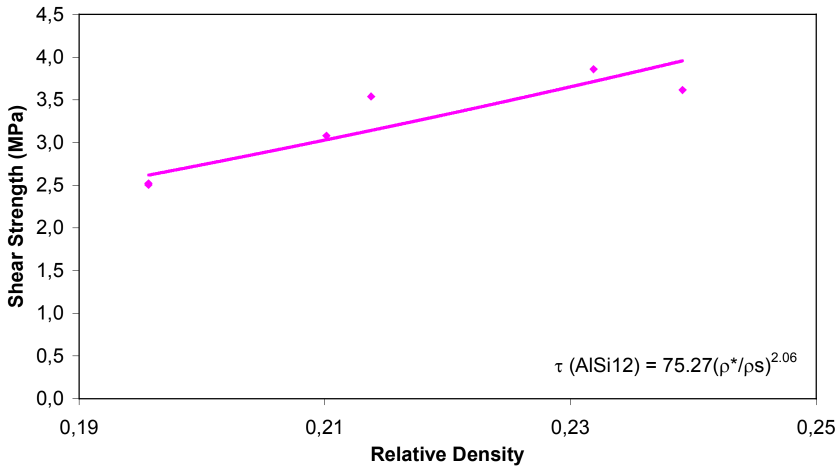

Fig. 12: Shear strength of AlSi 12 foam

(test results and approximation with $Const_{Shear}$ = 75.27 and n = 2.06)

Material	AlMg1Si (6061)	AlSi12
Test direction	L	L
ρ_{foam} [g/cm³]	0,58	0,59
τ_{max} [MPa]	3,22	3,19

Table 5: Shear strength of aluminium foams

Tensile Strength / Strain:

In general metal foams show a brittle behaviour under tensile load. The strains at rupture indicate that elastic deformation is followed by a very narrow plastic strain with an instant rupture of the foam (see single values in Table 4). The individual pores act as fracture initiating notches which means in turn that the sensitivity to notches in part geometry is limited. For the design of metal foam parts or cores for foam filled structures significant tensile loads should be avoided.

Material	AlMg1SiCu (6061)	AlMg1SiCu (6061)
ρ_{foam} [g/cm^3]	0,31	0,458
σ_{max} [Mpa]	2,79	6,06
$\sigma_{rupture}$ [Mpa]	2,76	5,99
$\sigma_{elastic}$ [Mpa]	1,11	3,31
ε_{max} [%]	0,84	0,89
$\varepsilon_{rupture}$ [%]	0,90	0,92

Table 6: Tensile properties of 6061 foams

Acoustic Properties – Loss Factor for Structure Borne Sound

When compared to the solid material, foams exhibit improved sound absorption characteristics as well as better vibration damping capabilities.

The loss factor η for structure borne sound indicates what fraction of the vibratory (reversible) mechanical energy is lost (i.e., converted into heat) in one cycle of the vibration. In Fig. 13 the loss factor of an aluminium foam is displayed in denpendecy of the foam density. With decreasing foam density the loss factor increases. In comparison to the dense material aluminium foams show a significant higher loss factor which indicates the foams better applicability for structure borne sound sensitive structures.

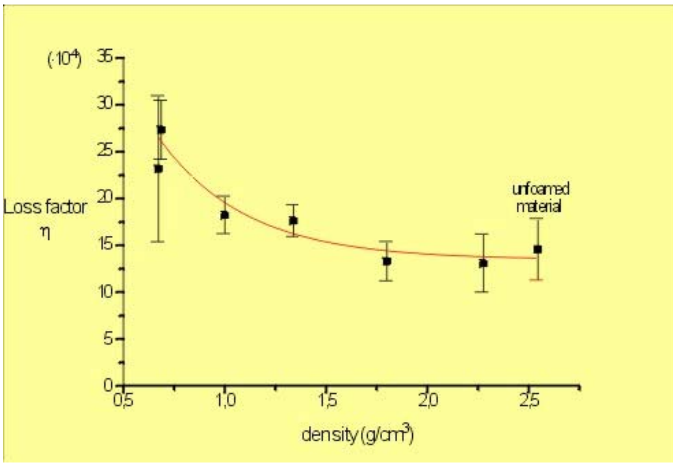

Fig. 13: Loss factor for AlSi 12 foams with different densities[4]

[4] „Damping properties of aluminium foams“
Banhart, Baumeister, Weber in Materials Science and Engineering A 205 (1996)

Thermal Properties

Thermal properties of FOAMINAL® show the same dependencies on the temperature as the conventional dense material.

Alloy composition	AlMg1SiCu (6061)	AlMg1SiCu (6061)	AlSi7	AlSi7	AlSi12
Heat treatment	age hardened	„as foamed“	„as foamed“	„as foamed“	„as foamed“
Density [g/cm^3]	0,6	0,6	0,55	0,63	0,6
Thermal conductivity [W/mK]	18,4 (RT) - -	18,4 (RT) - -	6,1 (50°C) 6,9 (100°C) 7,7 (200°C)	7,8 (50°C) 8,8 (100°C) 9,8 (200°C)	16,7 (RT) - -
Heat capacity [kJ/kgK]	0,92	0,92	0,9	0,9	0,88
Coefficient of thermal expansion [$10^{-6}/K$]	23,1	23,1	-	-	19,9 ... 20,6

Table 7: Thermal properties of aluminium foams

General Description

Aluminium foam sandwich (AFS) is a composite material of three layers. Surface layers are conventional aluminium wrought alloys or steel sheets with a metallic bond to the aluminium foam core layer in between.

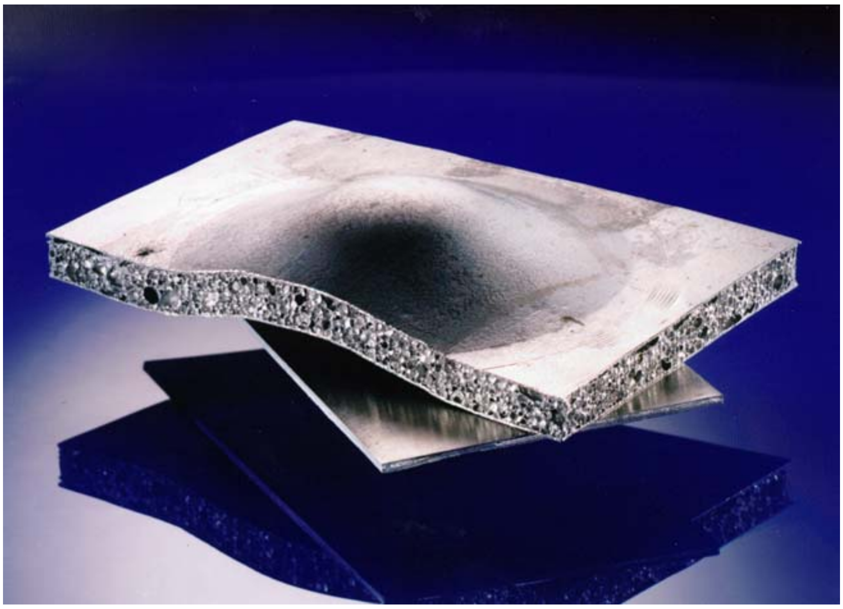

Fig. 14: Aluminium foam sandwich (foamed and unfoamed, steel face sheets)

Production Process

The production process for aluminium foam sandwich consists of two main steps (Fig. 15). After the compaction of the powder mixture the two surface layers of conventional material are roll cladded to the semifinished foamable material. This semi-finished composite with a core layer of foamable material can be shaped by conventional forming techniques, like bending, pressing, deep-drawing etc. After the final geometry is achieved the formed part is heated above foaming temperature and the semifinished foamable core layer expands. After cooling to room temperature the three dimensional AFS material is finished.

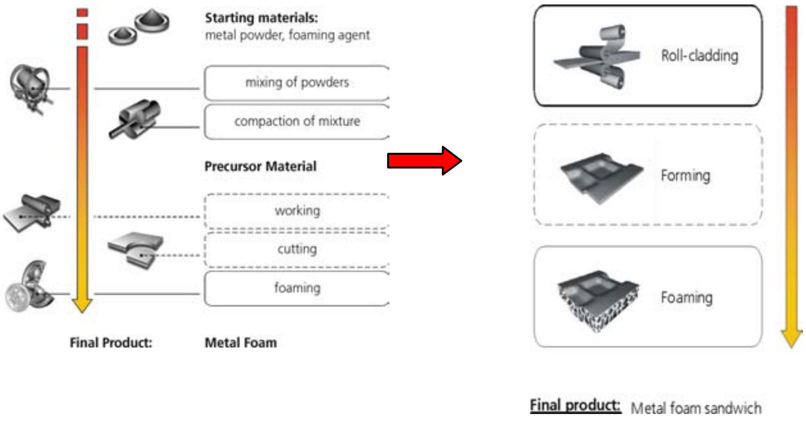

Fig. 15: Production process for aluminium foam sandwich

Properties

Aluminium foam sandwich is characterized by an outstanding performance in terms of bending stiffness. These remarkable stiffnesses directly derive from the foam core layer. Semi-finished not foamed AFS sheets have comparable bending stiffnesses as conventional aluminium alloy sheets. During core layer expansion the thickness of the AFS sheet increases which directly increases the moment of interia and thus the bending stiffness. Comparing same weight sheets of AFS and conventional aluminium alloy the moment of intertia and therefore the bending stiffness of the AFS are significantly higher.

The properties of aluminium foam sandwich strongly depend on the material and the thickness of the surface and core layers. Materials combination, thickness of surface layers as well as foam core layer and the foam core density can be adjusted to customers requirements, but the thickness of aluminium face sheets should not be less than 0.7 mm. During development of the AFS technology the following standard material dimensions have been established:

- total thickness : 11 mm
- thickness of surface layers : 1 mm
- foam core layer density: 0.4 g/cm^3
- overall AFS density: 0.8 g/cm^3
- surface weight: 9.23 kg/m^2

Since the AFS is a composite of three layers the mechanical properties depend on the loading direction. The following table gives an overview of standard AFS properties:

Loading direction	Orthogonal to surfaces	Parallel to surfaces
Young's Modulus [GPa]	2.5	15
$\sigma_{tension,\ max}$ [MPa]	4	90
$\sigma_{comp,\ max}$ [MPa]	8	n.a.
τ_{max} [MPa]	4	n.a.
Thermal expansion [1/K]	23 x 10^{-6}	
Heat conductivity [W/mK]	12	235
Heat capacity (20 ... 100 °C) [J/gK]	0.9	
Max. operation temperature [°C]	430	
Sound absorption (1 ... 10 kHz) [%]	30	
Electrical conductivity [m/Ωmm^2]	2.1	34

Table 8: Properties of standard AFS

Shaping and AFS Processing

The semi-finished composite with the foamable core layer can be formed by conventional forming techniques. As a result of the roll-cladding process all layers are strain-hardened to a certain level. This has to be taken into account for every subsequent forming step, eventually a soft annealing step can be necessary.

Three dimensional shaping of the semi-finished foamable composite in general is no problem for foam expansion. It has to be kept in mind that the core layer expands significantly in contrast to the surface layers. Therefore closed profiles, U-profiles and similar geometries made from one sheet of semi-finished foamable composite can not be foamed properly. In all cases both not foamable surface layers retain in their shape during heating. For proper foam expansion at least one surface layer needs to have a certain degree of freedom for movement in vertical direction to the part surface (foaming direction).

In general the processing for AFS production is comparable to the FOAMINAL® - processing. By heating the semi-finished composite above foaming temperature the foamable core layer is expanded. After cooling down the aluminium foam sandwich part is finished.
If narrow shape tolerances are required or complex formed parts are to be produced the semi-finished composite needs to be heated in a supporting mould. During heating the core layer becomes liquid (foam expansion) and the surface layers at least soften. Without support the part can deform due to gravity force influence during heating.

After expansion of the foam core layer the AFS parts can be shape calibrated and/or locally densified by pressing. However, it has to be taken into account that the foam core layer may be deformed during these forming steps.